EVALUATION ON EMPIRICAL MODELS FOR THE PREDICTION OF CYCLONE EFFICIENCY

Jolius Gimbun[1], T.G. Chuah[2], Thomas S. Y. Choong[2] and A. Fakhru'l-Razi[2]

[1]Faculty of Chemical and Natural Resources Engineering, University Collage of Engineering and Technology Malaysia, KUKTEM, Bandar MEC, 25200 Kuantan, Pahang

[2]Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor

E-mail: chuah@eng.upm.edu.my

ABSTRACT

A numerical simulation on cyclone collection efficiency is presented. The simulations deal with tangential inlet cyclones with relatively low solids loading (<10 g/m³) and for cyclone diameter from 0.01 to 3 m. The calculations are realised with four models presented in the literature, namely Koch and Licht [7], Lapple [8], Li and Wang [9] and Iozia and Leith [9]. The models were evaluated over a wide range of operating conditions. The result from this work will help the cyclone designer or operation engineer to select the most suitable cyclone model depending on inlet flow rate, temperature and pressure used.

Keywords : *Cyclone Prediction, Gas-solid Separators, Grade Efficiency, Temperature*

1.0 INTRODUCTION

Cyclones are devices that employ a centrifugal force generated by a spinning gas stream to separate particles from the carrier gas. Their simple design, low maintenance costs, and adaptability to a wide range of operating conditions such as sizes and flow rates make cyclones one of the most widely used particle removal devices. By using suitable materials and methods of construction, cyclones may be adapted for use in extreme operating conditions: high temperature, high pressure, and corrosive gases. Cyclones are important particle removal devices in both engineering and process operations.

An inaccuracy in cyclone efficiency prediction may result in an inefficient design of cyclone separators. Models to predict the behaviour of cyclones are usually empirical. It remains largely a process of trial and error, since empirical cyclones models are only applicable to specific cyclone geometries. This study reviews the prediction four different cyclone efficiency empirical models, namely Lapple [8], Koch and Licht [7], Li and Wang [9], and Iozia and Leith [4]. All predictions are compared with published measurements from literature over a wide range of operating conditions. The result from this work will provide guidance to the cyclone designer or operation engineer to select the most appropriate cyclone model depending on inlet flow rate, temperature and pressure used. In this study, models are solved numerically using Microsoft Excel spreadsheet.

2.0 CYCLONE DESIGN

The reverse flow cyclones with tangential inlet, Figure 1, are most often used for industrial gas cleaning [9]. The dimensions of the cyclones used in this study are given in Table 1. The inflowing fluid rotates within the main body of the chamber and is constrained to follow a spiral flow path. Any particles suspended within the fluid are subjected to an enhanced radial acceleration. The larger particles migrate outwards to the cone wall where they travel in a downward spiral to the base of the chamber and exit at the underflow. The smaller particles migrate more slowly and therefore their distribution across the flow changes little. Those in the centre are captured in the upward flow and spiral upward and out through the vortex finder. The remainder is discharged with the coarse fraction at the underflow.

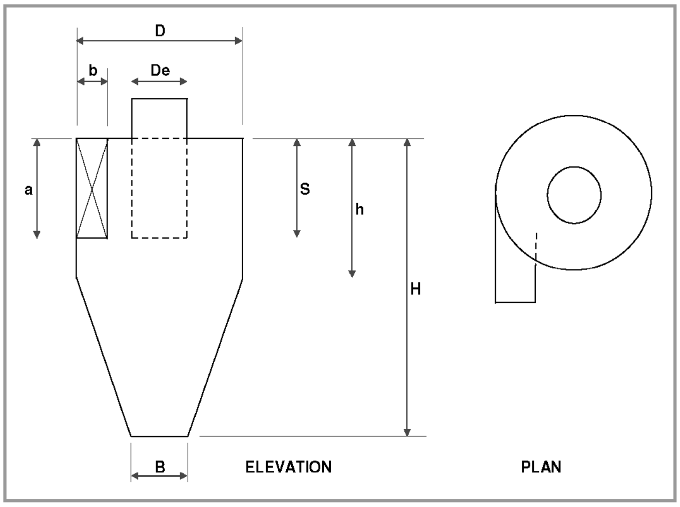

Figure 1: Tangential cyclone configuration

Table 1: Cyclone geometry used in this simulations

Geometry	*a/D*	*b/D*	*De/D*	*S/D*	*h/D*	*H/D*	*B/D*
Stairmand high efficiency	0.5	0.2	0.5	0.5	1.5	4	0.375
Kim and Lee [6] cyclone 1	0.33	0.225	0.257	1.157	1.447	3.05	0.482
Parker et al. [11] cyclone 2	0.38	0.19	0.31	1.13	1.81	4.31	0.38
Exxon [2]	0.57	0.25	0.5	0.75	2.00	4	0.45

3.0 CYCLONE EFFICIENCY EMPIRICAL MODELS

3.1 IOZIA AND LEITH MODEL

Iozia and Leith (1990) logistic model is a modified version of Barth (1956) model which is 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*. Core length, z_c, and core diameter, d_c, are given as

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

$$z_c = H - S \text{ for } d_c < B \qquad \text{for } d_c < B \qquad (1b)$$

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

The addition made by Iozia and Leith on the original Barth (1956) model are the core length z_c and slope parameter β expression which is derived based on the statistical analysis of experimental data of cyclone with D = 0.25 m. The collection efficiency η_i of particle diameter d_{pi} can be calculated from

$$\eta_i = \frac{1}{1+(d_{pc} / \bar{d}_{pi})^{\beta}} \qquad (3)$$

where d_{pc} is the 50% cut size given by Barth (1956)

$$d_{pc} = \left[\frac{9\mu Q}{\pi p_p z_c v^2_{t\max}}\right]^{0.5} \qquad (4)$$

3.2 LI AND WANG MODEL

The Li and Wang (1989) 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. Li and Wang model was developed based on the following assumptions:

- The radial particle velocity and the radial concentration profile are not constant, for uncollected particles within the cyclones.
- Boundary conditions with the consideration of turbulent diffusion coefficient and particle bounce re-entrainment on the cyclone wall are:

$$c = c_0, \text{ at } \theta = 0 \qquad (5)$$

$$D_r \frac{\partial c}{\partial r} = (1 - \alpha)wc, \text{ at } r = D/2 \qquad (6)$$

- The tangential velocity is related to the radius of cyclone by: uR^n = constant.

The concentration distribution in a cyclone is given as:

$$c(r,\theta) = \frac{c_0(r_w - r_n)\exp\left\{-\lambda\left[\frac{1}{K(1+n)} r^{1+n}\right]\right\}}{\int_{r_n}^{r_w} \exp\left\{\frac{1}{K(1+n)} r^{1+n}\right\} dr} \qquad (7)$$

where

$$k = \frac{(1-n)(\rho_p - \rho_g)d^2 Q}{18\mu b(r_w^{1-n} - r_n^{1-n})} \qquad (8)$$

and

$$\lambda = \frac{(1-\alpha)kw_w}{D_r r_w^n} \qquad (9)$$

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

$$\eta_i = 1 - \exp\{-\lambda\theta_1\} \qquad (10)$$

where

$$\theta_1 = 2\pi (S + L) / a \qquad (11)$$

3.3 KOCH AND LICHT MODEL

Koch and Licht (1977) collection theory recognized the inherently turbulent nature of cyclones and the distribution of gas residence times within the cyclone. Koch and Licht describe particle motion in the entry and collection regions with the additional following assumptions:

- The tangential velocity of a particle is equal to the tangential velocity of the gas flow, i.e. there is no slip in the tangential direction between the particle and the gas.
- 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.

$$\eta_i = 1 - \exp\left\{-2\left[\frac{G\tau_i Q}{D^3}(n+1)\right]^{0.5/(n+1)}\right\} \qquad (12)$$

where

$$G = \frac{8k_c}{k_a^2 k_b^2} \qquad (13)$$

$$n = 1 - \left\{1 - \frac{(12D)^{0.14}}{2.5}\right\}\left\{\frac{T + 460}{530}\right\}^{0.3} \qquad (14)$$

$$\tau_i = \frac{\rho_p d^2_{pi}}{18\mu} \qquad (15)$$

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 (1951) model was developed based on force balance without considering the flow resistance. Lapple 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 (1951) to calculate a 50% cut diameter, d_{pc}, is

$$d_{pc} = \left[\frac{9\mu b}{2\pi N_e v_i (\rho_p - \rho_g)} \right]^{\frac{1}{2}} \tag{16}$$

where N_e is the number of revolutions

$$N_e = \frac{1}{a}\left[h + \frac{H - h}{2} \right] \tag{17}$$

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

$$\eta_i = \frac{1}{1 + (d_{pc} / \bar{d}_{pi})^2} \tag{18}$$

4.0 RESULT AND DISCUSSION

4.1 EFFICIENCY PREDICTION UNDER AMBIENT TEMPERATURE

Ray *et al*. [12], Kim and Lee [6], Dirgo and Leith [15], and Parker *et al*. [11] presented experimental data obtained at room temperature. Comparison between the calculated cyclone efficiency from the models and the experimental data are shown in Figures 2 to 4. Li and Wang [9] prediction is found to agree much better with Kim and Lee [5], Dirgo and Leith[5], and Ray *et al*.'s [12] data, compared to models developed by Koch and Licht, Iozia and Leith [4], and Lapple [8] as shown in Figures 2 to 4. Lapple's model yields less accurate fitting to the experimental data (curves are flatter at higher particle size), so as Koch and Licht's model [7]. Both model considerably underestimates efficiency for large particles and overestimates efficiency for small particles to a lesser extent. Lapple model [8] is unable to fit well to any experimental data. This is possibly because of Lapple model simply assumes that a particle that entering the cyclone is evenly distributed across the inlet opening and particle that travels from the inlet half width to the cyclone wall is collected with 50% efficiency. Unjustified assumptions of complete and uniform mixing of uncollected dust at any height in the cyclones may contribute to the discrepancy between experimental data and the Koch and Licht [3] predictions. Mothes and Loffler [10] (1982) experimental findings further support the fact that there is indeed a concentration gradient in the radial direction of the cyclones.

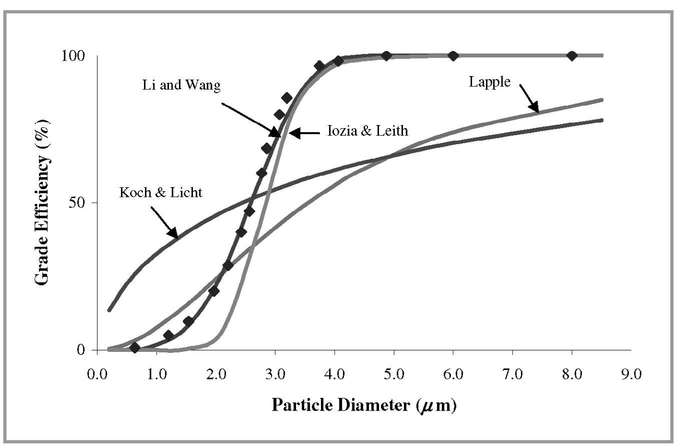

Figure 2: Calculated and measured collection efficiencies for Stairmand high efficiency cyclone (T = 293 K, v_i = 11 m/s, D = 0.4 m). Experimental Data from Ray et al. [12]

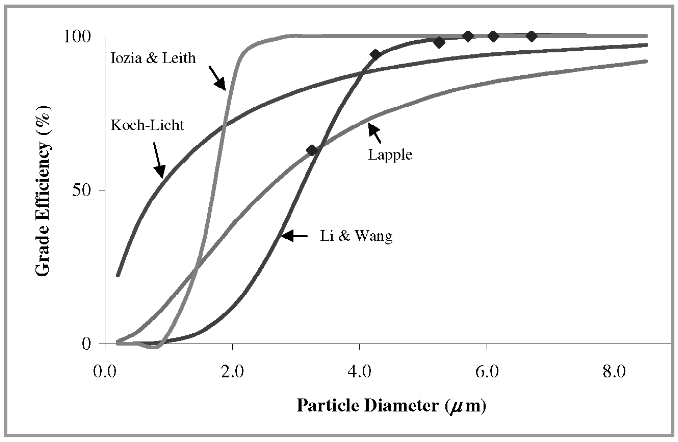

Figure 3: Calculated and measured collection efficiencies [6] cyclone (P = 1 bar, T = 293 K, v_i = 4.25 m/s, D = 0311 m). Experimental Data from Kim and Lee [6]

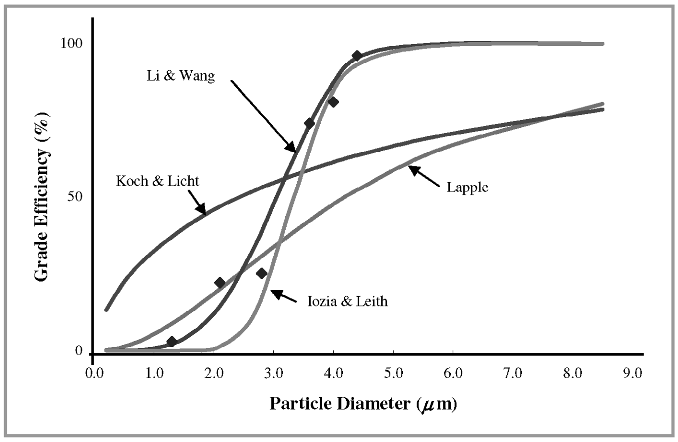

Figure 4: Calculated and measured collection efficiencies for Stairmand high efficiency cyclone (P = 1 bar, T = 293 K, v_i = 15 m/s, D = 0.305 m). Experimental data from Dirgo and Leith [4]

Iozia and Leith [4] logistic model predicted satisfactory the efficiency for cyclone of diameter 0.4 and 0.305 m as shown in Figures 2 and 4. For smaller cyclone diameter, the prediction of Iozia and Leith model [4] is not satisfactory. It considerably overestimates the grade efficiency for D = 0.0311 and 0.058 m as shown in Figures 3 and 5. The reason of this disagreement maybe caused by the generalised form of core length, z_c in Iozia and Leith model which is developed based on the statistical analysis of experimental cyclone data from cyclone of D = 0.25 m. Therefore, the prediction of the model is only satisfactory for cyclone diameter around this range.

4.2 EFFICIENCY PREDICTION UNDER DIFFERENT OPERATING CONDITIONS

In order to predict the influence of operating temperature on cyclone performance, a few researcher such as Parker *et al. [11]* and Dietz [2] has carried out the experiment under extreme temperature and pressure operating conditions. The comparison of the four selected model predictions and the experimental data are discussed below.

Under high pressure and low inlet velocity the prediction of Li and Wang [9] model is reasonably good except in the prediction for smaller particles as shown in Figure 5. This may be due to assumption of turbulent flow inside the cyclone used in Li and Wang model. The inlet velocity of 1.4 m/s used in Parker *et al*. [11] experiment is not large enough to produce a turbulent flow inside the cyclone. Under this condition Koch and Licht model is also found to be rather close to the experimental data for large particle sizes, as shown in Figure 5.

The data [2] concern experiments at temperature above 1000 K and pressure up to 6 bar. It appears that the Lapple model shows a good prediction of cyclone efficiency under high temperature and high pressure conditions, as shown in Figures 6 and 7. The Koch and Licht model gives reasonable prediction under these conditions. Li and Wang, and Iozia and Leith [4,9] models were unable to predict accurately the cyclone efficiency under these conditions.

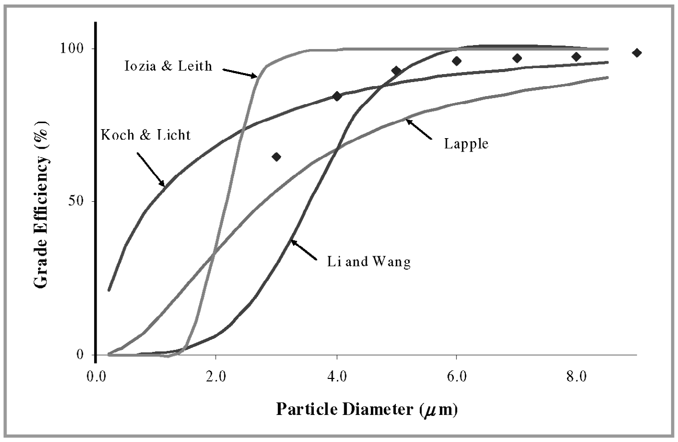

Figure 5: Calculated and measured collection efficiencies for Parker et al. (1981) cyclone II (P = 5.16 bar, D = 0.058 m, v_i = 1.4 m/s, T = 293 K). Experimental data from Parker et al. (1981)

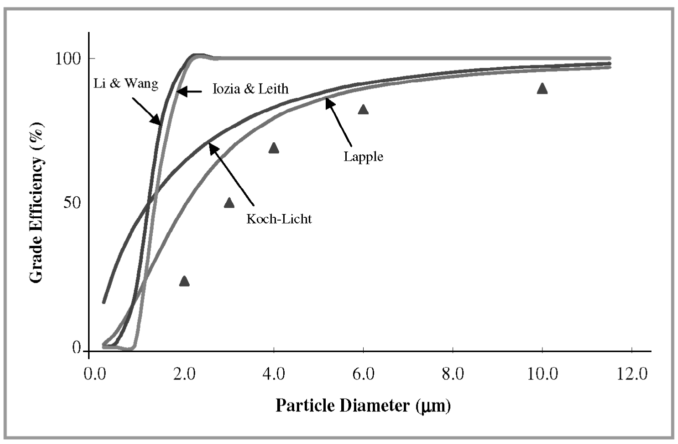

Figure 6: Separation efficiency of Exxon cyclone at high temperature and pressure (P = 6 bar, T = 1221 K, v_i = 54.8 m/s, D = 0.178 m). Experimental data from Dietz (1981)

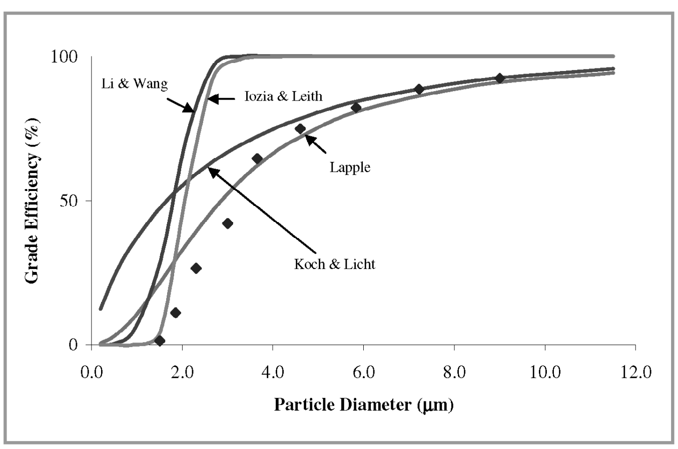

Figure 7: Separation efficiency of Exxon cyclone at high temperature (P = 1 bar, T = 1144 K, v_i = 24.4 m/s, D = 0.178 m). Experimental Data from Dietz (1981)

5.0 DOMAIN OF THE MODELS RELIABILITY

The results obtained in the previous section is summarised in Table 2. This may provide useful guidance to researches and engineers for the selection of a suitable model for the prediction of cyclone performance.

Table 2: Domain of reliability of the models for separation efficiency prediction

Operating Conditions	Suitable model
Ambient Temperature (T = 293 K) and Pressure < 2 bar	Li and Wang
Low inlet velocity	Koch and Licht
High Pressure	Koch and Licht
High Temperature	Lapple
High Temperature and Pressure	Lapple

6.0 CONCLUSION

Li and Wang [9] model's prediction on cyclone efficiency is excellent under the room temperature condition. The Li and Wang model produces a better fit to the Ray's and Kim and Lee experimental data. Lapple and Koch and Licht models considerably underestimate efficiency for large particles and overestimates efficiency for small particles to a lesser extent. Iozia and Leith [4] logistic model show a good agreement with an experimental data for the cyclone size range of D = 0.25 – 0.4m. However it is unable to predict correctly the efficiency for small cyclone (D < 0.1m). Iozia and Leith model is only suitable for efficiency prediction of cyclone diameter around 0.25 m.

Under the combination of extreme condition such as very high temperature and pressure, Lapple model shows a reasonably good prediction. Koch and Licht [7] model shows a good cyclone efficiency prediction under high pressure operating condition. While, under high operating temperature, Lapple model is shown to be the most reliable model for cyclone efficiency prediction. ■

NOTATION

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 donates 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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