INFLUENCE OF DESIGN AND OPERATING PARAMETERS ON SEPARATING THE COARSE WHEAT BRAN BY CYCLONE

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ABSTRACT

*Experimental study and predicted models were used to investigate the effect of cyclone geometry and operating parameters such as cone height (30, 50 and 70 cm), vortex finder length (0, 10, 20, 30 and 40 cm), dipleg length (25, 40 and 55 cm) and inlet air velocity (14, 16, 18 and 20 m/s) on separating the coarse wheat bran from air stream. The performance parameters via cut-off diameter (d_{50}), overall collection efficiency (η_o) and pressure drop (ΔP) were evaluated to determine the appropriate design of the cyclone under local operating conditions. The results showed that, ΔP increased with the increase of inlet air velocity and cone height. The optimum operating and design parameters at cone height of 70 cm were inlet air velocity 14 m/s and vortex finder length 40 cm, which lead to high η_o 99.93 % and low ΔP 80.63 Pa. While at cone height of 50 cm, the optimum operating and design parameters were: inlet air velocity 18 m/s under vortex finder length 40 cm which lead to high η_o 99.97 % and low ΔP 121.52 Pa. whereas the cone height 30 cm and vortex finder length zero cm were undesirable because they have low η_o. The d_{50} decreased with increase inlet air velocity and lead to increase η_o; for instance at cone height of 30 cm the d_{50} of **Lapple** model were 31.95, 29.88, 28.17 and 26.73 µm for coarse wheat bran at inlet air velocity 14, 16, 18 and 20 m/s, respectively. Moreover the statistical indicators presented that the **Hoffmann & Stein** model was the best model and more validation to predict coarse wheat bran η_o at cone height 30 and 50 cm. The **Lapple** model was the best model and more validation to predict coarse wheat bran η_o at cone height 70 cm. There is a wide range of the optimum η_o depend on the design, operating parameters and the price of the separated material and this is subject to the operator's decision; in other words balancing operating economics cost and the price of the separated material.*

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NOMENCLATURE

A : cross-sectional areas of the inlet, m^2
a : cyclone inlet height, m
b : cyclone inlet width, m
D : cyclone vortex finder (exit pipe) diameter, m
d_{50} : cut-off diameter of particle which is collected with 50 % efficiency, µm or m
D_b : cyclone cone-tip or dust outlet or dipleg diameter, m
D_c : cyclone body (cylindrical part) diameter, m
d_c : core diameter. M
d_{pi} : average particle diameter of the ith fraction, µm
f : friction factor.
h_1 : cyclone cylindrical part (body) height, m
h_2 : cyclone conical part height, m
h_3 : cyclone dust outlet (dipleg) length, m
H_{cs} : height of the control surface extending from the bottom of the vortex finder to the cyclone bottom or core length, m
H_t : cyclone total height (total height), m
l : physical length, m
L_e : distance between the outlet section and the cylindrical barrel top.
L_i : distance between the inlet section and the cyclone center.
l_n : natural vortex length (inner vortex), m
M_c : mass of collected dust, kg
M_e : mass of emitted dust, kg
M_f : mass of feed dust, kg
m_i : mass fraction of particles in the *i*th size range, %
MRD : mean relative deviation (statistics), %
N : number of cyclones in the system, in parallel.
n : number of measurements (statistics).
N_e : number of effective turns in a cyclone
P_{si} : static pressure at inlet, N/m^2
P_{so} : static pressure in outlet, N/m^2
Q : gas volume flow rate, m^3/h or m^3/s
R : cyclone radius ($D_c/2$), m
r : Pearson correlation coefficient (statistics).
R_d : radius of dust outlet or dipleg ($D_b/2$), m
RMSE : root mean square error (statistics)
RSEP : relative standard error of prediction (statistics), %
R_x : radius of vortex finder (D/2), m
S : cyclone vortex finder or gas outlet length, m
V : flow velocity in streamwise direction, m/s
v_i : average air velocity at the cyclone inlet, m/s
v_{rcs} : redial velocity at control surface, m/s
$V_{t\ max}$: maximum air tangential velocity, m/s
$v_{\theta cs}$: tangential velocity at the control surface CS, m/s
$v_{\theta w}$: wall velocity (the velocity outside CS), m/s
x : experimental value.
y : predicted value.
β : slope parameter.

ΔP : pressure drop in the cyclone, N/m^2
η_i : collection efficiency for any particle size, %
η_o : overall collection efficiency, %
θ : cone angle.
μ_g : dynamic viscosity (air viscosity), 1.81×10^{-5}, kg/m . s or N . s /m^2
ρ_g : gas density (air) 1.18, kg/m^3
ρ_p : particle density, kg/m^3

INTRODUCTION

Many industrial sectors like food and fodder processing, agricultural processing, minerals processing, plastic and chemical industry and many more run processes contained huge amounts of particles or powder in their processes. Particulate matter or powders are tiny particles of solid particle suspended in a gas (**Juengcharoensukying *et al.*, 2017**). Cyclone is still the most popular cleaning device used in many industries to separate particulate matter from process gas streams. Cyclone is considering a simple device that uses centrifugal force to separate the particles from the conveying gas **(Hoffmann and Stein, 2008).** In spite of the principle of the cyclone separators is simple, the flow of the mixture inside the cyclone is very complex. So, many experimental, theoretical and computational studies have been reported in the literature aimed understanding, predicting and improving the performance of cyclones in terms of pressure drop and overall collection efficiency **(Elsayed, 2011).**

Chuah *et al.* (2003) concluded that pressure drop is a function of the square of inlet velocity, so too high a velocity will cause an excessive pressure drop. On the other hand, too low a velocity would cause a low efficiency. A very high inlet velocity would decrease the collection efficiency because of increasing turbulence and re-entrainment of particles. Generally it was found that the optimum operating velocity is around 18 m/s. Meanwhile, **Shepherd and Lapple (1939)** reported that, the range of practicable cyclone inlet velocity is around 15 – 30 m/s. Moreover **Wang *et al.* (2006)** used inlet velocity of the mixture (gas - particle) 20 m/s. **Abdel-Hadi (2014**) investigated the effect of inlet air velocity on the flow field behavior and performance of the cyclone to separate coarse wheat bran, the results showed that, the overall collection efficiency was function to increase inlet velocity in the range from 9.3 to 18.5 m/s. The best inlet velocity was 18.5 m/s where the overall collection efficiency values were 96.4, 98.9, 98.5, 98.3 and 98.7 %; the pressure drop values were 1173, 1324, 1249, 1137 and 1419 Pa at vortex finder lengths 0, 5, 10, 15 and 20 cm, respectively. The pressure drop in a cyclone is the difference of static pressure between the inlet and outlet, which can be written as follows according to (**Chen and Shi, 2007)**:

$$\Delta P = P_{si} - P_{so} \quad (1)$$

Azadi *et al.* (2010) reported that, cyclones are characterized by cut-off diameter (d_{50}) which defines the particle size for which the cyclone collection efficiency is 50 %. It is important to know the cyclone cut-off diameter under certain operational conditions and geometry. Traditional cyclone literature has given direct empirical correlations for d_{50} based on the cyclone geometry and flow properties as listed in Table (1).

Table (1): Traditional cyclone literature for cut-off diameter (d_{50}).

Reference	Equation	Remarks
Lapple (1950)	$d_{50} = \sqrt{\frac{9\mu_g b}{2\pi\rho_p v_i N_e}}$	(2)
	$N_e = \frac{1}{a}\left[h_1 + \frac{h_2}{2}\right]$	(3)
Rietema (1959)	$d_{50} = \sqrt{\frac{\mu_g\rho_g Q}{(\rho_p - \rho_g)H_t\Delta P}}$	(4)
Iozia and Leith (1990)	$d_{50} = \sqrt{\frac{9\mu_g(Q/N)}{\pi\rho_p H_{cs}V_{t\,max}^2}}$	(5)
	$V_{t\,max} = 6.1\,V\left(\frac{A}{D_c^2}\right)^{0.61}\left(\frac{D}{D_c}\right)^{-0.74}\left(\frac{H_t}{D_c}\right)^{-0.33}$	(6)
	$V = \frac{Q/N}{A}$	
	$H_{cs} = (H_t - S) - \left(\frac{H_t - S}{(D_c/D_b) - 1}\right)\{(d_c/D_b) - 1\}$ For $d_c > D_b$	(7)
	$H_{cs} = (H_t - S)$ For $d_c < D_b$	(8)
Hoffmann & Stein (2008) and Elsayed & Lacor (2009)	$d_{50} = \sqrt{\frac{9v_{rcs}\mu_g D}{\rho_p v_{\theta cs}^2}}$	(9)
	$v_{rcs} = \frac{Q}{\pi D H_{cs}} = \frac{v_i ab}{\pi D H_{cs}}$	(10)
	$H_{cs} = (H_t - S) - h_2\,(R_x - R_d)/(R - R_d)$	(11)
	$v_{\theta cs} = \frac{v_{\theta w}\left(\frac{R}{R_x}\right)}{\left(1 + \frac{H_{cs}R\pi f v_{\theta w}}{Q}\right)}$	(12)

The main performance characteristics of cyclone separators are fractional efficiencies (η_i) and overall collection efficiency (η_o). Fractional efficiency is defined as the fraction of particles of a given size collected in the cyclone, compared to those of that size going into the cyclone. it can be expressed as a function of particle diameter (d_{pi}). Several equations have been developed to predict the fractional and overall collection efficiency in cyclones through correlation equations as listed in Table (2).

Table (2): Literature equations for predict the fractional and overall collection efficiency in cyclones.

Reference	Equation	Remarks
	Fractional efficiency (η_i)	
Lapple (1951a)	$\eta_i = 1/\left[1+\left(\frac{d_{50}}{d_{pi}}\right)^2\right]$	(13)
Iozia and Leith (1990)	$\eta_i = \frac{1}{1+(d_{50}/d_{pi})^{\beta}}$	(14)
	Where:	
	$ln(\beta) = 0.62 - 0.87ln[d_{50}(cm)] + 5.21ln\left(\frac{A}{D_c^2}\right) + 1.05\left[ln\left(\frac{A}{D_c^2}\right)\right]^2$	(15)
	Overall collection efficiency (η_o)	
Wang (2004)	$\eta_o = \sum \eta_i m_i$	(16)

Zhu and Lee (1999) reported that the physical length played a significant role in the particle collection characteristics, so the vortex finder length could be optimized. The outer vortex weakens and changes its direction at a certain axial distance (l_n) from the vortex finder. This distance is usually called the natural length of the cyclone as shown in Fig. (1) (**Wang *et al.*, 2003 and Cort´es & Gil, 2007)**. A good cyclone separator design has equal natural vortex length (l_n) and physical length (l = H_t - S); overall length of the barrel and cone minus the vortex finder length **(Swaray and Hamdullahpur, 2004)**. **Büttner (1999)** found two distinct types of cyclone operation. First type, when the operation with $l_n \geq l$; the vortex end reaches the bottom of the cyclone. Second type, when the operation with $l_n < l$ the collection performance is poor, because the vortex end attaches to the cyclone wall, disturbing the solids strands that are already separated and decreasing the efficiency through instability and re-entrainment. Table (3) shows different correlation used to calculate the natural vortex length of the cyclone.

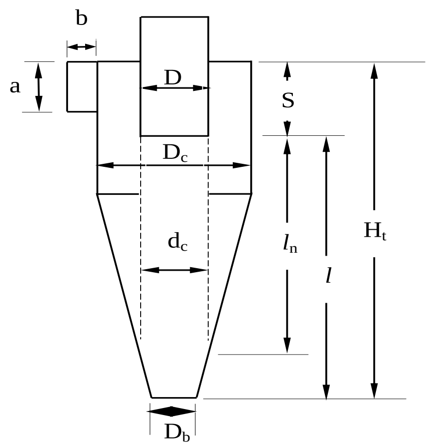


Fig. (1): Cyclone inner vortex core dimensions (Wang *et al.*, 2003).

Table (3): The empirical models in the literature used for calculating the natural vortex length of the cyclone.

Reference	Equation	Remarks
Alexander (1949)	$\frac{l_n}{D_c} = 2.3 \frac{D}{D_c} \left(\frac{D_c^2}{A}\right)^{1/3}$	(17)
Bryant *et al.* (1983)	$\frac{l_n}{D_c} = 2.26 \left(\frac{D}{D_c}\right)^{-1} \left(\frac{D_c^2}{A}\right)^{-0.5}$	(18)
Ji *et al.* (1991)	$\frac{l_n}{D_c} = 2.4 \left(\frac{D}{D_c}\right)^{-2.25} \left(\frac{D_c^2}{A}\right)^{-0.361}$	(19)

The main objectives of this study are to investigate the effect of cyclone geometry and operating parameters such as cone height, cyclone total height, vortex finder length, dipleg length and inlet air velocity on performance parameters via d_{50}, η_o and ΔP. Assess the predictive validity of some literature correlations in comparison with the measured data to put the data into better use with the existing theories.

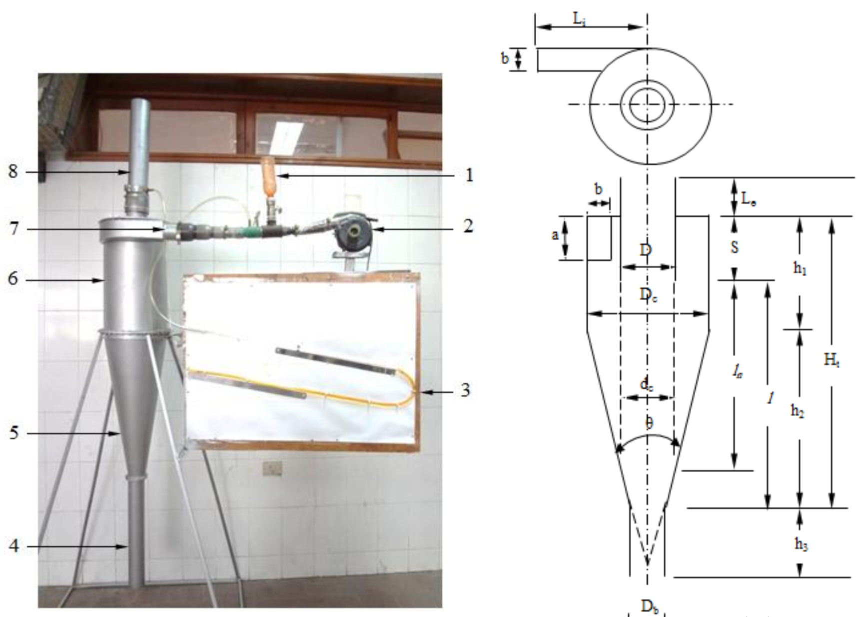
MATERIALS AND METHODS

Experimental Setup

The experimental unit was designed and constructed at the workshop of the Agricultural Engineering Department, Faculty of Agriculture, Suez-Canal University. The parts of unit were fabricated from galvanized steel sheet of 1.5 mm thickness. Cutting and welding of cyclone parts were done by laser technology in a local workshop in 10th of Ramadan city industrial. The dimension and specification of the experimental unit are tabulated in Table (4) and the overview in Fig. (2). The inclined differential water-manometer for pressure drop measurement was made from the silicone tube internal and external diameter of 6.5 and 9.5 mm, respectively. The differential water-manometer was fixed between inlet and outlet air as shown in Fig. (2). The air supply unit was connected to the air inlet pipe and a set of input dust particle. The air velocities (m/s) were measured by air velocity meter.

Table (4): Dimension and specification of the experimental setup.

Parameter	Description	Values	Unit
D_c	Cyclone body diameter	30	cm
h_1	Cyclone cylindrical part height	50	cm
b	Cyclone inlet width	7.2	cm
a	Cyclone inlet height	7.2	cm
D	Vortex finder diameter	9.2	cm
D_b	Dipleg diameter	7.7	cm
Experimental parameters under study			
h_2	Cyclone conical part height	30, 50 and 70	cm
h_3	Dipleg length	25, 40 and 55	cm
H_t	Cyclone total height	80, 100 and 120	cm
S	Vortex finder length	0, 10, 20, 30 and 40	cm
v_i	Inlet air velocity	14, 16, 18 and 20	m/s



(A) (B)

Fig. (2): Cyclone annexed to the water-manometer (A) and design & nomenclature (B).

The bulk density of coarse wheat bran was determined in laboratory, it was 213 kg/m^3. The obtained result of coarse wheat bran was in range bulk density from 176 to 256 kg/m^3 according to **(Appel, 1985).** The particle size distribution were measured using a vibrating sieve shaker machine consists of sieves stacked vertically with sizes ranging from 60 to 2500 μm. The percentage of full-size distribution for average particle diameter (μm) is shown in Fig. (3).

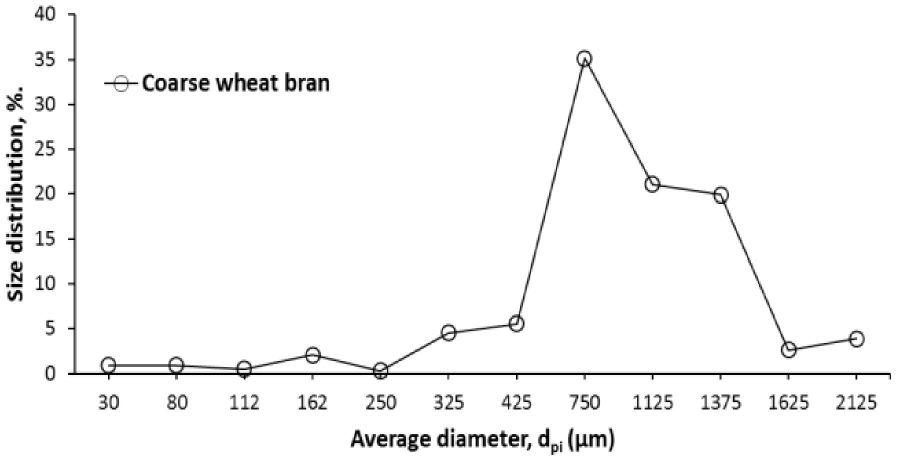


Fig. (3): The percentage of full- size distribution for coarse wheat bran.

<u>Overall Collection Efficiency Measurements (η_o)</u>

Hoffmann and Stein (2008) stated that, the three particle fractions (dust feed, collected and emitted) were representing their masses by the symbols M_f, M_c and M_e, respectively. The η_o is simply calculated as the mass fraction of the feed materials (dust) and collected by the cyclone:

$$\eta_o = \frac{M_c}{M_f} \times 100 = \left(1 - \frac{M_e}{M_f}\right) \times 100 = \frac{M_c}{M_c + M_e} \times 100 \qquad (20)$$

<u>Statistical indicators</u>

Some statistical indicators were applied to compare and validate the measured with predicted results as illustrated in Table (5). In general, maximum value of (r) indicates a better fit of the predicted model. On the other hand, the minimum values of (*MRD*, %), (*RSEP*, %) and (*RMSE*) were selected as a best fit model **(Tantar *et al.*, 2014)**.

Table (5): Some statistical indicators to compare and validate the measured with predicted results

Statistical Indicators	Equation	Reference	Remarks
mean relative deviation MRD, %	$MRD(\%) = \left[\sum_{j=1}^{n} \frac{\lvert x-y \rvert}{x}\right] \times \frac{100}{n}$	**Chen and Morey (1989)**	(21)
relative standard error of prediction *RSEP*, %	$RSEP\ (\%) = 100 \times \sqrt{\frac{\sum_{j=1}^{n}(x-y)^2}{\sum_{j=1}^{n} x^2}}$	**Ghasemi and Niazi (2005)**	(22)
root mean square error *RMSE*	$RMSE = \sqrt{\frac{\sum_{j=1}^{n}\left(x_j - y_j\right)^2}{n}}$	**Jachner *et al.* (2007)**	(23)
Pearson correlation coefficient (r)	$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2}\sqrt{n\sum y^2 - (\sum y)^2}}$	**Spatz (2008)**	(24)

Measuring the Diameter of Emitted Dust

In order to measure the diameter of emitted dust, microscopic slides and its coverslips were cleaned with 45 % acetic acid and then dried in the oven for a few minutes at 40 ^{o}C. The Haupt's adhesive according to **(Yeung *et al.*, 2015)** was mounted on the slide and then exposed to the vortex finder against the air outlet stream to adhere the emitted dust. Then a drop of the Canada balsam (Sigma) was dropped carefully above the dust specimen and gently covered with a coverslip with slop angle of 45^{o} to avoid the presence of air bubbles. The slide was dried in the oven at 50 to 55 ^{o}C about three weeks **(Palma, 1978)**. The emitted dust was photographed using the Microscope (Leica, DM500). The diameter (µm) of dust was measured by micrometer eyepiece slides.

RESULTS AND DISCUSSION

Pressure Drop (ΔP)

The relationship between inlet air velocity and pressure drop under different cone heights is illustrated in Fig. (4). The maximum ΔP 161.3, 181.7 and 250.8 Pa were recorded at inlet air velocity of 20 m/s, cone heights of 30, 50 and 70 cm under vortex finder lengths of 40, 40 and 0 cm and dipleg lengths of 55, 25 and 25 cm, respectively. Meanwhile the minimum ΔP were 60.2, 63,6 and 80.6 Pa recorded at inlet air velocity of 14 m/s, cone heights of 30, 50 and 70 cm under vortex finder lengths of 10, 30 and 40 cm and dipleg lengths of 25, 55 and 55 cm, respectively.

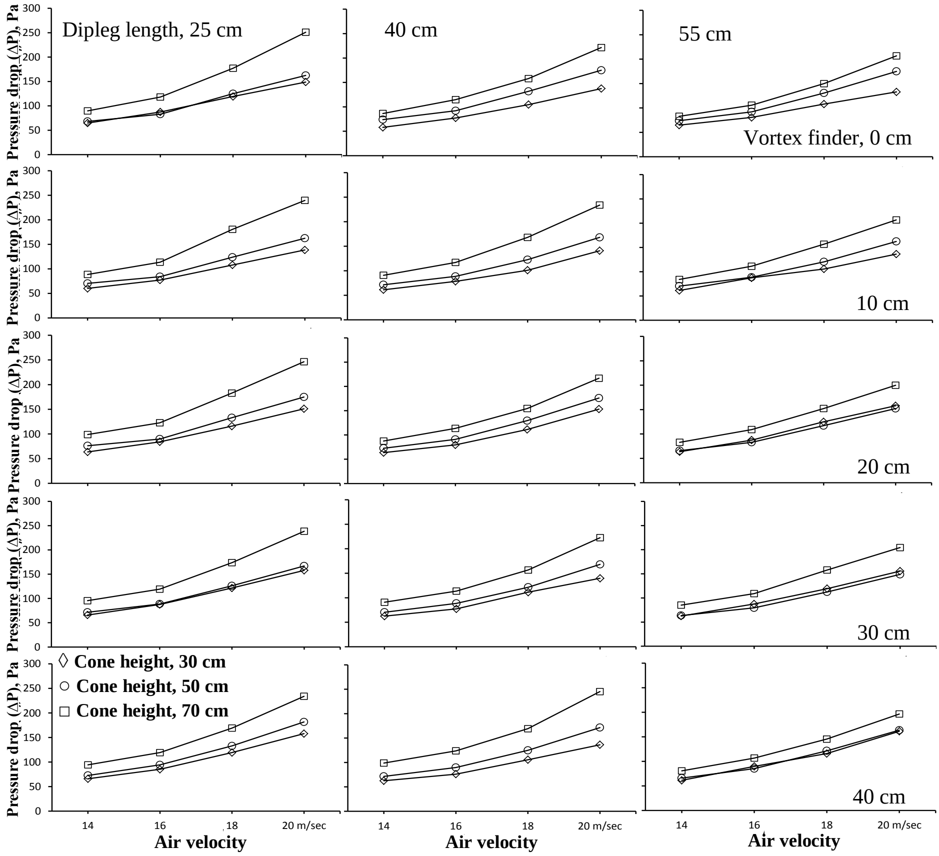


Fig. (4): Effect of inlet air velocity on measured pressure drop at different cone heights, vortex finder lengths and dipleg lengths

In general, the measured ΔP increased with the increase of inlet air velocity and cone height; the obtained results were in agree with (**Chuah *et al.*, 2006 and Juengcharoensukying *et al.*, 2017**). Moreover, the results showed that, the pressure drop were increased with increasing cyclone size according to **(Azadi *et al.*, 2010**) and the observed results showed that, also the effect of both vortex finder length and dipleg length on ΔP had a tiny effect and neglected, these results were in agree with (**Elsayed, 2011)**.

<u>Efficiency of Cyclone</u>

The main performance characteristics of the cyclone are η_o and η_i. The factor affecting on η_o based on a design parameters number of effective turns (N_e) in a cyclone, l_n, l, h_2, S and h_3 and factor based on operation parameters are v_i, ΔP and d_{50} (**Schnell & Brown, 2002; Hoffmann & Stein, 2008; Tan, 2008 and El-Batsh, 2013).**

Number of effective turns (N_e)

The number of effective turns (N_e) which calculated for three cone heights, according to **Lapple** model equation (3) is shown in Fig. (5).

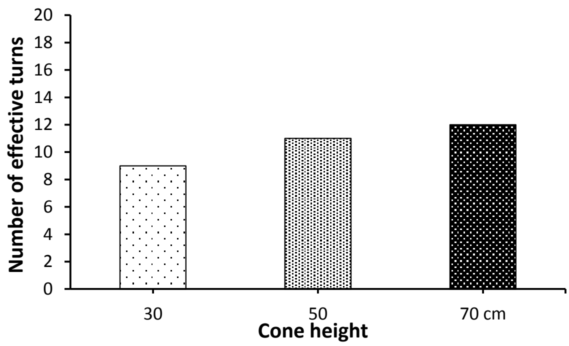


Fig. (5): Number of effective turns in the cyclone for three cone heights

As shown in the Fig. (5) the N_e increased with increase the cone height. A more effective turns of the air stream result in a higher collection efficiency, according to **(Lapple, 1950)**.

Natural vortex length (l_n) and physical length (l)

The comparative of the results of l_n were 60, 50 and 30 cm according to **(Alexander, 1949; Bryant *et al.*, 1983 & Ji *et al.*, 1991),** respectively. Table (6) illustrates the l_n and l at different cone heights and vortex finder lengths. The l_n according to **(Alexander, 1949**) equal and longer than the l; were 60 $\geq$ 60, 50 and 40 cm at vortex finder lengths of 20, 30 and 40 cm, respectively, at cyclone cone height of 30 cm. While at cyclone cone height of 50 cm the l_n equal the l only at vortex finder length of 40 cm. Meanwhile, at the cyclone cone height of 70 cm the l_n lower than the l at all vortex finder lengths. The good design when the $l_n \geq l$ and H_t/D_c ratios within 2-10 lead to high η_o. At cone height of 30 cm the $l_n \geq l$ and the ratios were 2.6, 3.3 and 4 at cone heights of 30, 50 and 70 cm, respectively. These results are in agree with **(Büttner, 1999)**. This means that when the S increase lead to decrease of l, increase l_n and η_o at the same H_t.

Table (6): The natural vortex length and physical length at different cone heights and vortex finder lengths according to (Alexander, 1949).

Cone height, cm Total height, cm		30 80	50 100	70 120	Natural vortex finder (l_n), cm
		Physical length (*l*), cm			
Vortex finder length, cm	0	80	100	120	60
	10	70	90	110	60
	20	**60**	80	100	60
	30	**50**	70	90	60
	40	**40**	**60**	80	60

The selection of S was ideal in the cone height of 30 cm, while in the cone heights of 50 and 70 cm, it should be selected greater than 40 cm. In general, higher η_o not only corresponds with increase l_n, but also with another variables such as the ratio between H_t/D_c, N_e, d_{50} and ΔP.

Measurement of overall collection efficiency

The overall collection efficiency (η_o) is usually coined to refer the mass fraction of solid at the inlet of cyclone recovered in the gas stream at the end of the cyclone (dustbin) expressed in percentage.

Generally, η_o increased with increase inlet air velocity at different cone heights, dipleg lengths and vortex finder lengths. For instance, at cone height 30 cm, dipleg length 25 cm and vortex finder length zero cm η_o values were 95.34, 96.05, 96.11 and 96.99 % at inlet air velocities of 14, 16, 18 and 20 m/s, respectively as shown in Fig. (6).

The obtained results were in agreement with **(Lapple, 1951$_b$ and Leith & Licht, 1972),** where increase inlet air velocity leads to decrease d_{50}, which was inversely proportional to the η_o. Otherwise η_o increased with increase cone height. For instance, under dipleg length 25 cm, vortex finder length zero cm and the inlet air velocity 14 m/s η_o values were 95.34, 95.45 and 96.21 % at cone heights of 30, 50 and 70 cm, respectively. The obtained results attributed to increase cone height that leads to decrease d_{50} and increase the N_e and *l* which caused increasing η_o according to **(Lapple, 1950 and Büttner, 1999)**.

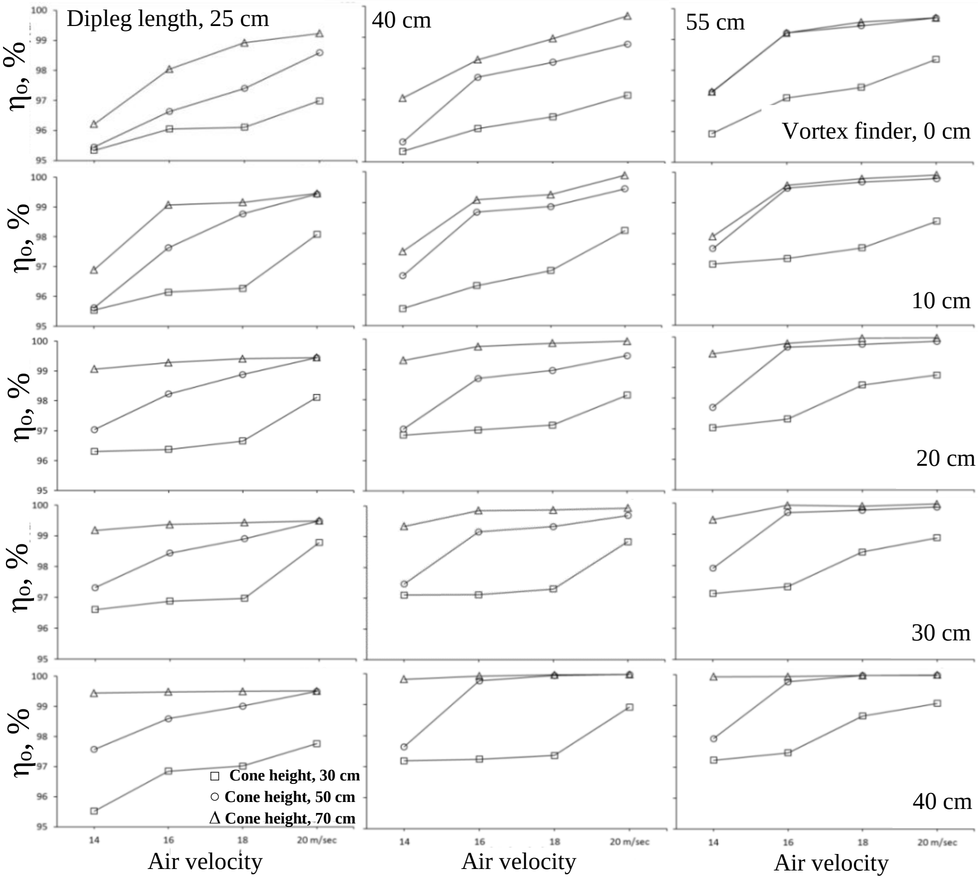


Fig. (6): The overall collection efficiency of coarse wheat bran under different inlet air velocities, cone heights, dipleg lengths and vortex finder lengths

Also in general, η_o increased with increase vortex finder length except at dipleg length of 25 cm, cone height of 30 cm and inlet air velocity of 14 m/s η_o values were 95.34, 95.54, 96.31, 96.61 and 95.25 % at vortex finder lengths of 0, 10, 20, 30 and 40 cm, respectively. While, η_o at dipleg length of 40 cm, cone height of 30 cm and inlet air velocity of 14 m/s were 95.34, 95.55, 96.84, 97.10 and 97.19 % at vortex finder lengths of 0, 10, 20, 30 and 40 cm, respectively. This result may be due to increase the vortex finder length with shorter cone height leads to reach the outer vortex (spiral motion) to the dustbin, which causes particles re-entrained into the vortex from the material already separated, thereby decrease η_o according to **(Hoffmann & Stein, 2008 and Qian *et al.*, 2006)**. The η_o can be improved significantly by changing the dust outlet geometry and cone height according to (**Obermair *et al.*, 2003)**. To avoid this phenomena in case coarse wheat bran, the cone height should be more than 30 cm or dipleg length more than 25 cm. In addition, η_o increased with increase dipleg length. For instance, under cone height 30 cm, inlet air velocity 14 m/s and vortex finder length zero cm, η_o were 95.34, 95.34 and 95.93 % at dipleg length 25, 40 and 55 cm, respectively. The minimum value of η_o was 95.34 % at minimum inlet air velocity 14 m/s, cone height 30 cm, vortex finder length zero cm and dipleg length 25 cm, while the maximum value was 99.99 % at maximum inlet air velocity 20 m/s, cone height 70 cm, vortex finder length 40 cm and dipleg length 55 cm. On the other hand, the maximum and minimum predicted d_{50} of coarse wheat bran for **Hoffmann & Stein** and **Lapple** models were 56 and 23 μm at minimum and maximum of the measured η_o, respectively, these results were in agree with (**Lapple, 1951$_b$ and Leith & Licht, 1972)**. Furthermore, the coarse wheat bran diameter, which emitted was equal or less than 10 μm as shown in Fig. (7) and less than predicted of d_{50} at maximum η_o. These results was in complete agreement with those obtained from **Cooper and Alley (2002**), which found that, the cyclones can reach efficiencies exceeding 99% for particles larger than 5 μm.

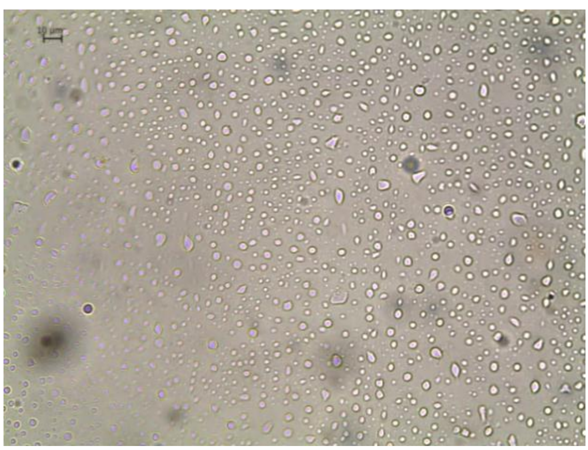


Fig. (7): The photographed emitted particles of coarse wheat bran using microscope (Leica, DM500)

<u>Calculating the cut-off diameter</u> (d_{50})

Four models were used to calculate the d_{50} according to (**Lapple, 1950; Rietema, 1959**; **Iozia & Leith, 1990 and Hoffmann & Stein, 2008)** due to the design of cyclone inlet was rectangular shape. Figure (8) displays the d_{50} of coarse wheat bran according to aforementioned four models at dipleg length of 25 cm.

The d_{50} was decreased with increase inlet air velocity at four models. The d_{50} was not affected by dipleg length, except **Rietema** model. The **Hoffmann** & **Stein** model was corresponding with radial velocity at the control surface (v_{rcs}), which depended on the vortex finder length as aforementioned in equation (9). The d_{50} decreased with increase vortex finder length, for instance at inlet air velocity 14 m/s and cone height 30 cm the d_{50} values were 56.42, 54.34, 52.24, 50.17 and 48.24 µm at vortex finder lengths of 0, 10, 20, 30 and 40 cm, respectively under dipleg length of 25 cm.

Meanwhile the d_{50} in this model increased with increase cone height. For instance, at inlet air velocity of 14 m/s and vortex finder length of zero cm; the d_{50} values were 56.42, 60.22 and 63.86 µm at cone heights of 30, 50 and 70 cm, respectively. The **Iozia** & **Leith** model was reverse **Hoffmann** & **Stein** model, on other words, the d_{50} increased with increase vortex finder length and decreased with increase cone height.

The calculation of **Iozia** & **Leith** model depends on the height of the control surface (H_{cs}). When H_{cs} increase, lead to decrease the d_{50} and vice versa as aforementioned in equation (5). For instance, at inlet air velocity of 14 m/s and cone height of 30 cm the d_{50} values were 8.25, 8.82, 9.53, 10.44 and 11.67 µm at vortex finder lengths of 0, 10, 20, 30 and 40 cm, respectively under dipleg length of 25 cm. Meanwhile, the d_{50} values at inlet air velocity of 14 m/s and vortex finder length of zero cm were 8.25, 7.95 and 7.70 µm at cone heights of 30, 50 and 70 cm, respectively. The **Rietema** model resulted in the lowest value of d_{50} compared to the other three models; the model depends on design and operation parameters via H_t and ΔP, respectively as aforementioned in equation (4). In other words, increase the inlet air velocity, H_t and ΔP lead to decrease the d_{50}. For instance, at vortex finder length of zero cm and cone height of 30 cm at inlet air velocities of 14, 16, 18 and 20 m/s at ΔP 64.73, 87.45, 119.24

and 148.77 Pa the d_{50} were 3.13, 2.88, 2.62 and 2.47 µm, respectively under dipleg length 25 cm.

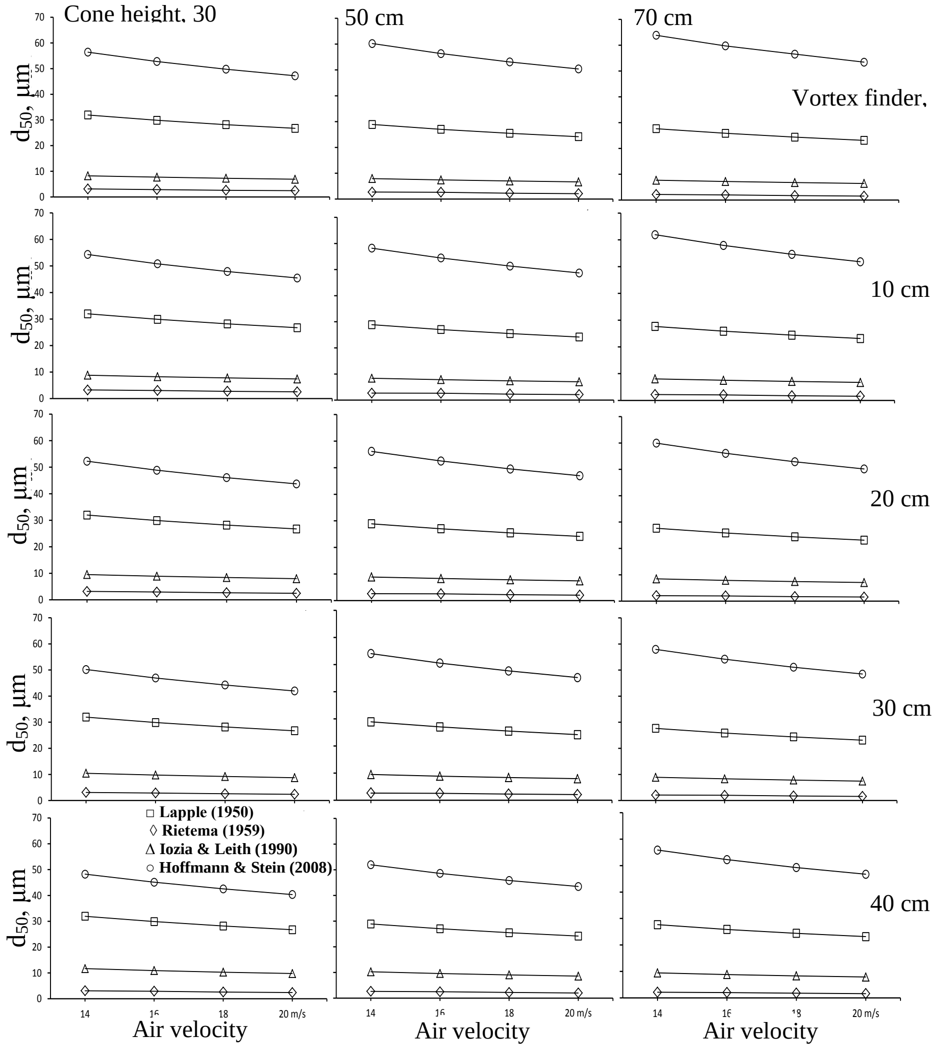


Fig. (8): The relationship between inlet air velocity and the d_{50} of coarse wheat bran at different cone heights and vortex finder lengths at dipleg length 25 cm

Meanwhile, at inlet air velocity of 14 m/s and vortex finder length of zero cm at ΔP 64.73, 68.14 and 89.72 Pa the d_{50} were 3.13, 2.73 and 2.17 µm at cone heights of 30, 50 and 70 cm, respectively. Most conventional ways for determining the predicted η_o of cyclone is by determining the

d_{50} of particle that needs to be separated. The d_{50} is inversely proportional to the η_o otherwise decreasing d_{50} leads to increase η_o **(Lapple, 1951b and Leith and Licht, 1972)**.

Predicted overall collection efficiency

In order to predict the η_o in cyclones based on equation (13) according to **(Lapple, 1951a)**, which was used before to calculate cut-off diameter d_{50}. Figure (9) and the results were illustrated comparison between the predicted and measured η_o of coarse wheat bran at different inlet air velocities, cone heights and vortex finder lengths under dipleg length 55 cm which was the best dipleg for measured of η_o.

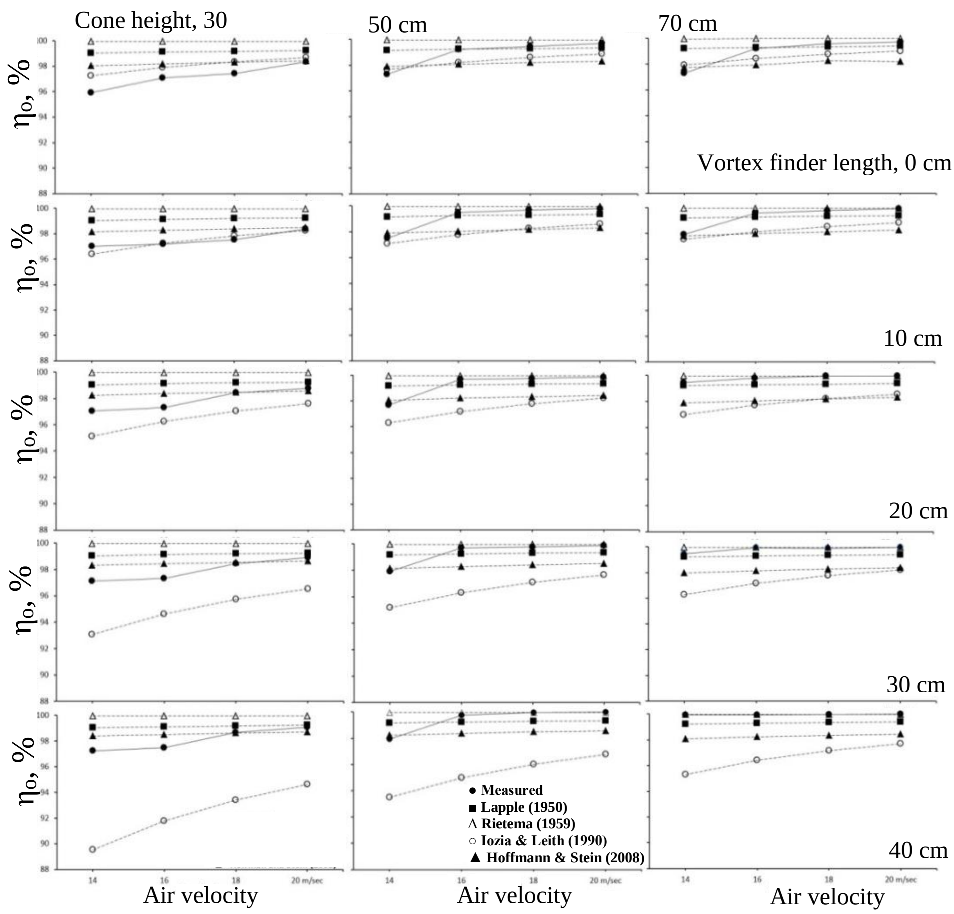


Fig. (9): Comparison between the predicted and measured of overall collection efficiency of coarse wheat bran at different inlet air velocities, cone heights and vortex finder lengths under dipleg length 55 cm

In general, in **Rietema** model the predicted η_o had the highest values and it was constant at different inlet air velocities, vortex finder lengths and cone heights comparing with other models. while in **Iozia & Leith** model the predicted η_o was increased with increase inlet air velocity and cone heights and decreased with increase vortex finder length. In case **Lapple** and **Hoffmann & Stein** models the predicted η_o had neglected increase at different inlet air velocities, vortex finder lengths and cone heights.
The results of models were compared to the measured values, which determined by weight method. To assess the predictive validity of the models in comparison to the measured η_o to find out the best model under different parameters. Table (7) shows some statistical indicators for empirical models to validate predicted with measured values of η_o.

Table (7): Some statistical indicators to validate predicted with measured values of overall collection efficiency of coarse wheat bran.

Statistics parameters		Measured values	Lapple	Rietema	Iozia & Leith	Hoffman & Stein
Cone height, 30 cm	**Mean**	97.18	99.15	99.95	95.87	98.41
	Std. deviation	0.972	0.07908	0.00645	2.38048	0.17135
	r	-	0.69775	0.01406	0.01994	**0.78941**
	MRD, %	-	2.036	2.859	2.240	**1.316**
	RSEP, %	-	2.233	3.017	2.937	**1.526**
	RMSE	-	2.171	2.932	2.854	**1.483**
Cone height, 50 cm	**Mean**	98.60	99.26	99.95	97.10	98.25
	Std. deviation	1.20858	0.07144	0.00360	1.36547	0.18819
	r	-	0.74380	0.61079	0.14225	**0.78772**
	MRD, %	-	0.986	1.384	1.910	**0.994**
	RSEP, %	-	1.342	1.830	2.281	**1.130**
	RMSE	-	1.323	1.804	2.250	**1.114**
Cone height, 70 cm	**Mean**	**99.30**	**99.30**	99.95	97.73	98.13
	Std. deviation	0.84734	0.06472	0.00446	0.93900	0.19182
	R	-	**0.52966**	0.44890	0.08579	0.75047
	MRD, %	-	**0.557**	0.672	1.728	1.310
	RSEP, %	-	**0.813**	1.074	2.056	1.378
	RMSE	-	**0.808**	1.066	2.042	1.369

As shown in Table (7), the **Rietema** and **Iozia & Leith** models were given an extreme result at different cone heights compared with measured of η_o because it had the lowest values of Pearson correlation coefficient (r) and at the same time had the highest values of (MRD, %), (RSEP, %) and (RMSE).

The **Hoffmann & Stein** model was more validation to predict η_o due to that the model had the highest values of (r) and at the same time had the lowest values of (MRD, %), (RSEP, %) and (RMSE) at cone heights of 30 and 50 cm. On the other hand, the **Hoffmann & Stein** model at cone heights of 30 and 50 cm was the best model to predict η_o, which the mean were 98.41 and 98.25 % and closed with the mean of measured η_o 97.18 and 98.60 %, respectively. While **Lapple** model was more validation at cone height 70 cm due to that, the model had the highest values of (r) and at the same time had the lowest values of (MRD, %), (RSEP, %) and (RMSE). Thereby, the **Lapple** model was the best model to predict η_o at cone height 70 cm because had the same value of the mean measured η_o 99.30 %. These results may be attributed to that, the predicted d_{50} at cone heights 30 and 50 cm of **Hoffmann & Stein** model meet with the requirements of the predicted η_o, on the other hand, **Lapple** model meet the requirements of the predicted η_o at cone height 70 cm as illustrated in Table (8).

Table (8): Comparison between the mean of the overall collection efficiency and cut-off diameter for measured and predicted models of coarse wheat bran at different cone heights.

Cone height, cm	Measured	Hoffmann & Stein model		Lapple model	
	η_o, %	η_o, %	d_{50}, µm	η_o, %	d_{50}, µm
30	97.18	98.41	47.76	99.15	29.18
50	98.60	98.26	51.3	99.26	26.40
70	99.30	98.13	54.9	99.30	25.27

Optimum Design and Operating Parameters

The η_o and ΔP are the two most important parameters for determining the design and performance of a cyclone separator; these parameters are intimately related and affected by each other. In order to determine the optimum η_o must be a balance between the economics of operation, maintenance and the price of the separated material; in other words tradeoff between higher η_o and low ΔP across the cyclone is essential according to (**Dirgo & Leith, 1985** and **Demir** ***et al.*****, 2016)**. The maximum η_o and minimum ΔP were observed as aforementioned under the influence of air velocity, cone height, vortex finder length, dipleg length and the interaction between them.

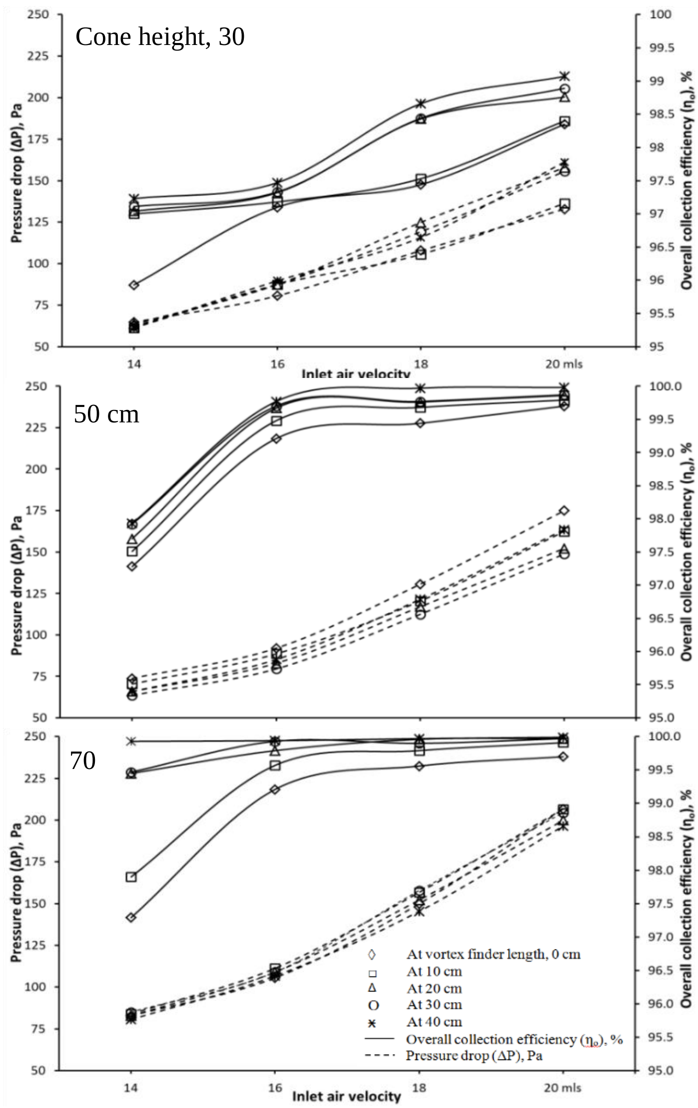


Fig. (10): Relationship between the measured overall collection efficiency and pressure drops of coarse wheat bran at different inlet air velocities, cone heights and vortex finder lengths under dipleg length 55 cm

As aforementioned the maximum measured η_o for coarse wheat bran was at cone height of 70 cm under dipleg length of 55 cm. As shown in Fig. (10), in cone height of 70 cm, the highest values of η_o, which were approximately constant ranged from 99.93 to 99.99 % obtained at vortex finder length 40 cm with inlet velocities from 14 to 20 m/s and the same time ΔP were increased rapidly from 80.63 to 196.47 Pa, respectively. These results are in agree with those obtained by **Pandya (2010)**, which found that the increase in inlet air velocity lead to increase η_o, rapidly increase ΔP and increases the manufacturing cost.

So that it is preferable to select the minimum inlet air velocity, which leads to minimum ΔP in order to decrease operating and maintenance costs. in other words, at cone height of 70 cm the optimum operating and design parameters were inlet air velocity of 14 m/s and vortex finder length of 40 cm, respectively. While, at vortex finder lengths of 30 and 20 or 10 cm, the optimum inlet air velocity were 16 m/s and 18 m/s, respectively. The vortex finder length zero cm had the minimum η_o and maximum ΔP and not preferred. At cone height 50 cm the maximum η_o were 99.97 and 99.98 % and ΔP 121.52 and 163.53 Pa at inlet air velocities 18 and 20 m/s, respectively under vortex finder length 40 cm. These results are in agreement with those obtained from **Shepherd and Lapple (1939)**, which found that the optimum operating velocity is around 15 ‐ 30 m/s.

While, in vortex finder lengths of 10, 20 and 30 cm, the η_o were 99.79, 99.86 and 99.87 % and ΔP 162.40, 152.18 and 148.77 Pa, respectively, at inlet air velocity of 20 m/s; on other words, the suitable parameters were 30 cm vortex finder length and inlet air velocity of 20 m/s. Meanwhile, vortex finder length of zero cm was not preferred at cone height of 50 cm. Meanwhile, the cone height of 30 cm was undesirable because it has low η_o and high ΔP.

CONCLUSIONS

The study carried out to evaluate the performance of local fabricated cyclone based on optimal operating and design conditions to obtain the highest overall collection efficiency (η_o) and the lowest operating pressure drop (ΔP) for separating coarse wheat bran. Moreover, some mathematical models were used to predict η_o and some statistical indicators for comparison and validation with measured results.

The experimental results were addressed as the following:

- The measured η_o and ΔP increase with increase inlet air velocity and cone height. The minimum ΔP was 60.2 Pa at inlet air velocity of 14 m/s and cone height of 30 cm, meanwhile, the maximum ΔP was 250.8 Pa at inlet air velocity of 20 m/s and cone height of 70 cm.
- The number of effective turns increased with increase the cone height, they were 9, 11 and 12 at cone heights of 30, 50 and 70 cm, respectively and it is reflected on increasing the η_o. Moreover, decreasing d_{50} with increase inlet air velocity lead to increase η_o at different cone heights, dipleg lengths and vortex finder lengths; for instance, at cone height of 30 cm the d_{50} of **Lapple** model were 31.95, 29.88, 28.17 and 26.73 µm for coarse wheat bran at inlet air velocities of 14, 16, 18 and 20 m/s, respectively, while, the mean of measured η_o were 96.38, 96.83, 97.24 and 98.29 %, respectively.
- The minimum value of the measured η_o coarse wheat bran was 95.34 % at minimum inlet air velocity of 14 m/s, cone height of 30 cm, vortex finder length of zero cm, dipleg length of 25 cm and predicted d_{50} 56 µm for **Hoffmann & Stein** model (more validation at cone height of 30 cm), while, the maximum value was 99.99 % at maximum inlet air velocity of 20 m/s, cone height of 70 cm, vortex finder length of 40 cm, dipleg length of 55 cm and predicted d_{50} 23 µm for **Lapple** model (more validation at cone height of 70 cm).
- The diameter of coarse wheat bran which emitted was equal or less than 10 µm and the same time less than predicted of d_{50} at maximum η_o. On other word, all the diameters more than 10 µm were captured and separated in the cyclone.
- The **Hoffmann & Stein** model was the best model and more validation to predict η_o of coarse wheat bran at cone height of 30 and 50 cm, which the mean were 98.41 and 98.25 % and closed with the mean of measured η_o 97.18 and 98.60 %, respectively. The **Lapple** model was the best model and more validation to predict η_o of coarse wheat bran at cone height of 70 cm because had the same value of mean measured η_o 99.30 %.
- The optimum operating and design parameters at cone height of 70 cm were inlet air velocity of 14 m/s and vortex finder length of 40 cm,

which lead to high η_o 99.93 % and low ΔP 80.63 Pa. While, at cone height of 50 cm the optimum operating and design parameters were at inlet air velocity of 18 m/s under vortex finder length of 40 cm which lead to high η_o 99.97 % and low ΔP 121.52 Pa. Meanwhile, the cone height of 30 cm was undesirable because it has low η_o and high ΔP.

- The vortex finder length of zero cm had the minimum η_o and maximum ΔP and not preferred at all cone heights.

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الملخص العربى

العوامل التصميمية والتشغيلية المثلى المؤثرة على عملية فصل ردة القمح الخشنة باستخدام السيكلون

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أجريت دراسة معملية على أداء سيكلون تم تصميمه وتركيبه فى قسم الهندسة الزراعية - كلية الزراعة - جامعة قناة السويس بهدف تقييمه للحصول على أعلى كفاءة كلية للتجميع (η_o) وأدنى فرق ضغط تشغيل (ΔP) فى فصل ردة القمح الخشنة. تمت دراسة بعض العوامل التشغيلية والتصميمية، مثل سرعة دخول الهواء (١٤، ١٦، ١٨ و ٢٠ م/ث)، ارتفاع المخروط (٣٠ ، ٥٠ و ٧٠ سم)، طول الوصلة التليسكوبية لخروج الهواء (٠ ، ١٠ ، ٢٠ ، ٣٠ و ٤٠ سم) وطول فتحة خروج المواد المجمعة (25 ، ٤٠ و ٥٥ سم) للتشغيل والتصميم الأمثل. علاوة على ذلك، تم استخدام بعض النماذج الرياضية للتنبؤ η_o وبعض المقاييس الإحصائية للمقارنة والتحقق من صحة القيم المتنبأ بها مع النتائج المقاسة.

وقد توصلت الدراسة إلى النتائج التالية:-

- تزداد الكفاءة الكلية المقاسة وفرق الضغط المقاس بزيادة سرعة دخول الهواء وارتفاع المخروط. وكان أقل فرق ضغط تشغيل 60.2 باسكال عند سرعة دخول الهواء ١٤م/ث وارتفاع المخروط ٣٠ سم، في حين كان أعلى فرق ضغط تشغيل 250.8 باسكال عند سرعة دخول الهواء ٢٠ م/ث وارتفاع المخروط ٧٠ سم.
- تزداد عدد اللفات الفعالة مع زيادة ارتفاع المخروط، حيث كانت ٩ و ١١ و ١٢ عند ارتفاع المخروط ٣٠ و ٥٠ و ٧٠ سم، على التوالي وتزداد مع ذلك η_o.

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علاوة على ذلك، تزداد η_o مع انخفاض d_{50} بزيادة سرعة دخول الهواء عند مختلف ارتفاعات المخروط وأطوال فتحة خروج المواد المجمعة وأطوال الوصلة التليسكوبية لخروج الهواء؛ على سبيل المثال، عند ارتفاع المخروط ٣٠ سم، كانت d_{50} لردة القمح الخشنة المحسوبة بنموذج Lapple 31.95، ٢٩,٨٨، ٢٨,١٧ و ٢٦,٧٣ ميكرون عند سرعة دخول الهواء ١٤، ١٦، ١٨ و ٢٠ م/ث، على التوالي، بينما كان متوسط الكفاءة الكلية المقياسة 96.38، 96.83، 97.24 و ٩٨,٢٩ ٪، على التوالي.

- كانت أقل قيمة للكفاءة الكلية المقاسة لردة القمح الخشنة ٩٥,٣٤٪ عند أقل سرعة دخول الهواء ١٤ م/ث، ارتفاع المخروط ٣٠ سم، وطول الوصلة التليسكوبية لخروج الهواء صفر سم، وطول فتحة خروج المواد المجمعة 25 سم، وكانت قيمة d_{50} المتنبأ بها المحسوبة بنموذج Hoffmann & Stein ٥٦ ميكرون (الأكثر تمثيلاً لقيم الكفاءة المقاسة عند ارتفاع المخروط ٣٠ سم)، بينما كانت أعلى قيمة ٩٩,٩٩ ٪ عند أعلى سرعة دخول هواء ٢٠ م/ث، أرتفاع مخروط ٧٠ سم، وطول الوصلة التليسكوبية لخروج الهواء ٤٠ سم، وطول فتحة خروج المواد المجمعة 55 سم وكانت قيمة d_{50} المتنبأ بها المحسوبة بنموذج Lapple 23 ميكرون (الأكثر تمثيلاً لقيم الكفاءة المقاسة عند ارتفاع المخروط ٧٠ سم).
- كانت أ قطار جسيمات ردة القمح الخشنة المنبعثة مع الهواء (التى لم يتم فصلها) والمقاسة بطريقة التصوير الميكروسكوبى تساوي أو أقل من ١٠ ميكرون وفي الوقت نفسه كانت أقل من أقطار d_{50} المتنبأ بها والمحسوبة عند أقصى η_o. وبعبارة أخرى، تم فصل جميع الأقطار التي تزيد عن ١٠ ميكرون وتجميعها في السيكلون.
- كان نموذج Hoffmann & Stein هو أفضل نموذج للتنبؤ η_o لردة القمح الخشنة عند ارتفاع مخروطي ٣٠ و ٥٠ سم، حيث كان متوسط الكفاءة المتنبأ بها ٩٨,٤١ و ٩٨,٢٥٪ فى حين كان متوسط الكفاءة المقاسة 97.18 و ٩٨,٦٠٪، على التوالي. بينما كان نموذج Lapple هو أفضل نموذج للتنبؤ بـ η_o لردة القمح الخشنة عند ارتفاع المخروط ٧٠ سم لتساوى متوسط القيمة المقاسة مع متوسط القيمة المتنبأ بها حيث كانت 99.30 ٪.
- كانت العوامل التشغيلية والتصميمية المثلى عند ارتفاع المخروط ٧٠ سم هي سرعة دخول الهواء ١٤ م/ث وطول الوصلة التلسكوبية لخروج الهواء ٤٠ سم، والتى أدت إلى أعلى η_o لردة القمح الخشنة ٩٩,٩٣٪ و أقل فرق ضغط تشغيل ΔP 80.63 باسكال.
- بينما كانت العوامل التشغيلية والتصميمية المثلى عند ارتفاع المخروط ٥٠ سم هي سرعة دخول الهواء ١٨ م/ث وطول الوصلة التلسكوبية لخروج الهواء ٤٠ سم، والتى أدت إلى أعلى η_o لردة القمح الخشنة ٩٩,٩٧٪ و أقل فرق ضغط تشغيل ΔP 121.52 باسكال.
- كان ارتفاع المخروط ٣٠ سم غير مناسب لإنخفاض η_o المقاسة لردة القمح الخشنة وأرتفاع فرق ضغط تشغيل ΔP المقاس عند كل سرعات دخول الهواء وأطوال الوصلة التلسكوبية لخروج الهواء وأطوال فتحة خروج المواد المجمعة.
- أدى استخدام طول الوصلة التلسكوبية لخروج الهواء صفر سم عند جميع أرتفاعات المخروط إلى إنخفاض η_o المقاسة لردة القمح الخشنة وأرتفاع فرق ضغط التشغيل ΔP المقاس.