ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

EXPERIMENTAL INVESTIGATION OF PRESSURE DROP IN GAS – SOLIDS CYCLONE SEPARATORS

M. A. Hosien and S. M. Selim

Department of Mechanical power Engineering, Faculty of Engineering
Minoufiya University, Shebin El –Kom, Egypt

ABSTRACT

The effects of cyclone size, inlet velocity, and particle size on the pressure drop across the gas –solids cyclone separator are presented experimentally. The experiments were conducted at four different cyclone sizes 0f 7.5,10,14 and 16mm, various particle sizes ranged from 70 to 510µm and various dust loading varied from 50 to 350$gram_{solids}/kg_{air}$. The results showed that the pressure drop across the cyclone decreases with increasing the cyclone size and increased considerable with increasing the inlet velocity. The results indicated that the pressure drop is found to increase sharply with increasing the particle size from 75µm to 225µm and then increases gradually with particle size larger than 225µm. The study reported very interesting correlation not previously addressed and represents an addition to knowledge which leads to the prediction of the actual pressure drop of dusty air from tests on clean air.

هذة الدراسة المعملية تبين تاثير حجم الفزازه، سرعة الدخول، و حجم الجزيئات علي هبوط الضغط خلال الفزازات الاعصارية والخاصة بتجميع العوالق الصلبه من تيار الغاز. اجريت التجارب على اربع احجام مختلفه للفزازة ةهي 7.5، 10 ، 14 و 16 mm احجام مختلفه للذرات تتراوح ما بين 70 الى 510µm، ونسب مختلفه للعوالق الصلبة تتراوح مابين 50 الى 350 $gram_{solids}/kg_{air}$. بينت النتائج ان هبوط الضغط خلال الفزازه يقل بزيادة حجم الفزازه ويزيد بزيادة سرعة دخول الهواء. النتائج بينت ان هبوط الضغط يزيد زيادة حادة بزيادة حجم الجزيئات من 75 الى 225µm ثم يزيد بالتدريج مع حجم الجزيئاب اكبر من 225µm. الدراسه استنتجت علاقه جديده تعتبر اضافةعلمية مهمه تبين انه من خلال عمل التجارب المعمليه على الهواء النقى يمكن التنبوء بالقيمة الحقيقية لهبوط الضغط في حالة وجود العوالق الصلبة في الهواء.

Keywords: Cyclone separators – Gas – solids – Particle size.

1. INTRODUCTION

Cyclones are widely used for various purposes, mainly for separating of the dense phase in a multi – phase flow. One of the reasons for the wide variety of applications of cyclones is due to the fact that they are easy to inspect and maintenance. They are easy to build, relatively economical to operate and can be adapted to a wide range of operational conditions. Fluid mixture enters the cyclone, makes a swirl motion and, due to the centrifugal forces, the dense phase of the mixture gains a relative motion in the radial direction and is separated from the main flow. The main performance characteristic of a gas – solids cyclone separator is the pressure drop. Many studies have performed on this difficult problem for determination of this characteristic, but these studies are successful for only a certain range of Reynolds number and geometrical ratios. Therefore, developing the pressure drop has been essentially based on experiments rather than mathematical models. A number of studies have been reported in literature, predicting pressure drop in cyclones. Biffin, et al. [1] proposed a new type of cyclone separator (Cardiff cyclone) combines two stages in one compact unit. They concluded that the Cardiff cyclone separator offers many advantages over conventional cyclones, for any given flow rate , the pressure drop across the Cardiff cyclone is consistently lower than that for Stairmand cyclone. De, et al. [2] investigated experimentally the pressure drop of simple plate type impact separators . Effects of air velocity, solid loading and inclined angle of impact blades on the pressure drop were discussed .Their experimental results demonstrated that this gas – solid separator had impact structure,. low pressure drop especially at low air velocity. Gil, et al. [3] introduced results about the effects of solid loading on the performance of a cyclone with bottom ash extraction of solids. Experiments conducted at inlet gas velocities ranged from 9 to 14 m/s, inlet solid loadings range from 30 to 230 g_{solids}/kg_{gas}, and bottom gas extraction percentages from 0.3 – 1.5 % . The results showed lower pressure drop values. For the cyclone design, a new correlation of pressure drop, including the influence of the solid loading is proposed. Also, based on the evolution of the pressure drop resistance coefficient, a new method for detecting cyclone fouling, not previously addressed, also presented. Fassani and Goldstein [4] studied the effect of high inlet solid loadings on cyclone pressure drop. The particles used were FCC catalyst. Their experiments were conducted at entrance velocities of 7, 18 and 27 m/s. The experimental results showed that, in the range of concentrations tested, the cyclone pressure drop for the solids laden air flow was about 47 % of that for clean air. Avci and Karagoz [5] performed theoretical analysis of pressure losses in cyclone separators under the consideration of geometrical and flow parameters including inlet geometry, surface roughness, velocity and particles concentration. The results obtained are compared with experimental values for different cyclone types. It was found that the proposed equation could be used to predict the pressure losses easily and it is worthy especially in industrial applications. Shin, et al. [6] conducted numerical and experimental studies for the development of high efficiency cyclone dust separator applicable to the extreme environments of high pressure of 6 bars and temperature up to 400^0 C. The calculated results predict well the general trend and its magnitude of the experimentally measured pressure drop with the condition of increased pressure and temperature as a function of flow rate. El- Batsh, et al. [7] investigated the flow filed and particle separation process in cyclones using numerical calculations as well as experimental measurements. In addition, the effects of cyclone size and inlet velocity on cyclone performance were investigated. The numerically predicted pressure drops and experimentally measured ones are compared with those calculated from the published semi empirical correlations. Chen, et al. [8] studied the influence of the bottom – contracted and edge – sloped vent – pipe on the pressure drop of a cyclone separator under different vent – pipe insert depth and different orientation of the sloped edge. The correlative results were also compared with the traditional linear – pipe – shaped cyclone separator. Results indicate that the cyclone inlet stream velocity has a strong influence on the pressure drop, and the results are similar to that of conventional cyclone. Namely, the pressure drop increases with increasing cyclone inlet velocity. Also, the pressure drop changes with the orientation of the sloped edge and they have the same rule of change, the maximum occurs at 90^0 and the minimum occurs at 270^0. Chen and Shi [9] analyzed the compositions of the pressure drop over a tangential inlet, reverse flow cyclone. It is assumed that two factors mainly contribute to the pressure drop, i.e., the local loss and the loss along the distance. By use of the measured results of the flow field in cyclones, the calculation methods for each loss have been developed. A universal model to predict the cyclone pressure drop is thus obtained simply by summing each loss. A detailed comparison between the calculated and experimental results show that this accurate model is suitable either for pure or for dust laden gases at normal or high temperature and can meet the requirement of most cyclone designs. From literature, there is a difficulty of theoretical treatment of dust collection phenomenon in cyclone; this is due to lack of experimental results to verification of theoretical treatment of cyclone collector performance. Therefore, experimental investigation of gas – solids cyclone separators performance for industrial applications operating conditions is required to establish these effects. To achieve these requirements the present research include, the effect of cyclone size, inlet velocity, and particle size on the pressure drop in gas – solids cyclone separators

2. EXPERIMENTAL WORK

2.1. Experimental Apparatus and Instrumentation

In the present study, the experimental data were obtained by conducting experiments using a specially designed and fabricated experimental facility. The schematic view of the test rig is shown in fig.1.The air supplied by two blowers providing a volume flow in the range of 14.5 –114.5 m^3/hr. Air flow rate measured using a calibrated orifice meter (2).This stream of air is mixed with the injected particles in the rectangular cross section inlet of the cyclone, and discharged tangentially to the tested cyclone (3). The pressure drop across both the cyclone and the orifice is measured using a multi – tube manometer connected to pressure taps of 1 mm inner diameter which are drilled normal to the wall. The deposited particles from the cyclone are collected in the hopper part (13). The air – particles mixture is adjusted with different controlling valves (9) and (16). The solid feeding system (4) consists of the solids supply reservoir and controlling valve. The solids supply has cylindrical shape with a conical end. The feeding control valve was calibrated with a dial scale to give a desired mass flow rate of feeding solids. Four sizes of cyclones are used, three of them were fabricated from metal sheet with different cyclone diameters 10,14,16 cm and the remaining one was fabricated from Perspex with 7.5 cm diameter. Fig. 2 shows the dimension ratios for Stairmand cyclone design used in this study.

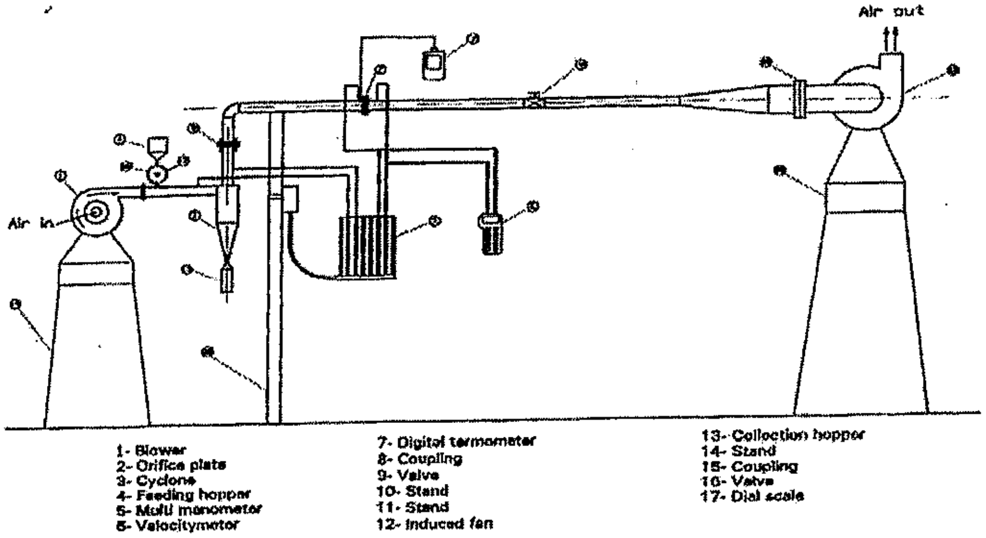

Fig. 1. Experimental test rig layout

2.2. Test Method

In order to study the effect of the particle size on the cyclone pressure drop, two solids materials were used in conducting experiments, commercial sand and white cement. Sand is used as the solid particles. The particle sizes in terms of median diameter were 70, 225, 360, 510μm and sand overall. The particle size distribution (PSD) is shown in fig. 3 and its density of about 1400 kg/m^3. The physical properties of the white cement are 70μm median diameters and density of about 1315 kg/m^3.

All solid samples were dried in an oven at 60^0 C before use. The experiments were carried out at almost equal room temperature and atmospheric pressure. The experimental readings were taken with more care, tabulated and plotted graphically. The experiments were carried out at dust loading values of 50, 80,100,125,200,275 and 350 g_{solids}/kg_{air} and inlet velocity varied from 5.3 to16.77 m/s.

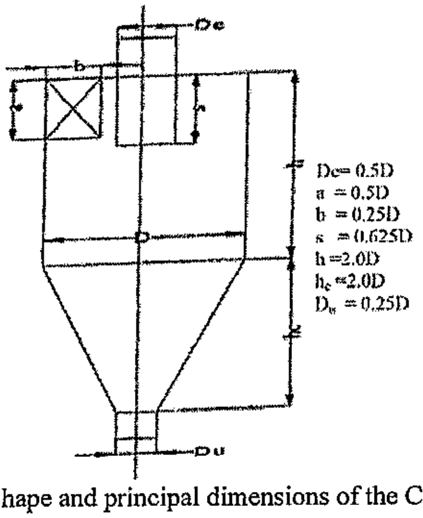

Fig.2. Shape and principal dimensions of the Cyclone

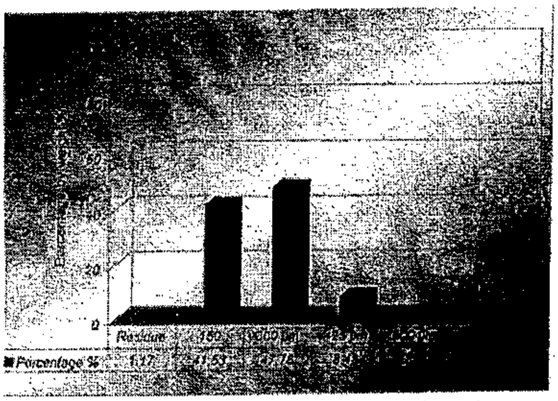

Fig.3 Particle size distribution of sand.

The forced and induced blowers were run for sufficient time till stable conditions of the flow have been established before the test was started. The delivery valve was adjusted at a certain opening to give the required flow rate. Solid particles of (sand) sample of a given particle diameter is weighed by the scale to determine its mass and is introduced into the solid supply reservoir .The calibrated solid control valve is adjusted at a certain opening to give the required solid flow rate. The measurements of the pressure drop in the cyclone, in the orifice meter, corresponding to the clean air condition were recorded. The solid loading valve opened and the measurement of the pressure drop in the cyclone, in the orifice meter, the time of solid loading and the air temperature in the inlet of the orifice meter corresponding to the condition were recorded. Solid particles were collected by the cyclone over a specified period of time and weighted by the scale to determine its mass flow rate. These observations of clean air and dusty air conditions were repeated for many other possible flow rates and the corresponding readings were determined.

2.3. Cyclone Performance Parameters

i – Pressure drop, $\Delta P = P_{si} - P_{so}$, uncertainty range, is 0.91 minimum and 3.36 maximum.

ii – Inlet velocity, $V_i = Q/A$ (m/s), uncertainty range, is 1.26 minimum and 4.7 maximum.

iii – Solid loading, $C_{si} = M_{si}/M_a$ (g_{solids}/kg_{air}), uncertainty range, is 0.026 minimum and 1.3 maximum.

3. EXPERIMENTAL RESULTS AND DISCUSION

3.1. Effect of Cyclone Size on the Pressure Drop

The pressure drop over a cyclone consists of a local loss and friction loss. The local loss includes an expansion loss at the cyclone inlet (due to expansion of air flow radially and axially after entering the cyclone, resulting in a local expansion loss), and a contraction loss at the entrance of the outlet tube (or vortex finder), (occurs because of an abrupt reduction of the flow area when air enters the outlet tube from the separation space of a cyclone). In the outlet tube, the air tangential velocity is still very high and the air flow is divided into two regions: a core region, in which the axial velocity is assumed as very small (i.e negligible), and an annular region, in which the axial velocity is uniformly distributed. The friction loss includes a swirling loss due to the friction between the air and the cyclone wall as a result of the air viscosity, and a dissipation loss of the air dynamic energy in the outlet. Therefore the cyclone size has a strong influence on the pressure drop in cyclones. The experimental results of the variation of pressure drop in four different sizes of cyclones at different solid loading ranged from 50 to 350 g_{solds} /kg_{air} and constant mean inlet velocity of 10.3 m/s are presented in figs. 4 to 7. Generally, these Figures indicate that increasing the cyclone size decrease the pressure drop across the cyclone and a sharp decrease in the pressure drop with increasing the cyclone size from 7.5 to10 cm is noted.

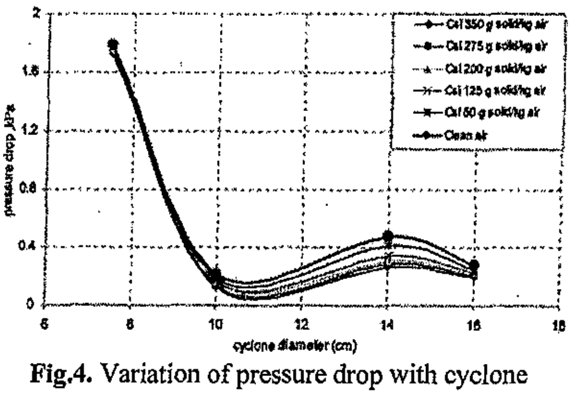

Fig.4. Variation of pressure drop with cyclone diameter for particle size (225μm) with different solid loading at constant inlet velocity of 10.3m/s.

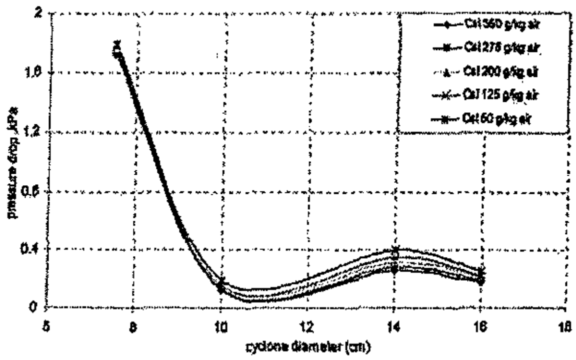

Fig.5. Variation of pressure drop with cyclone diameter for particle size (360μm) with different solid loading at constant inlet velocity of 10.3m/s.

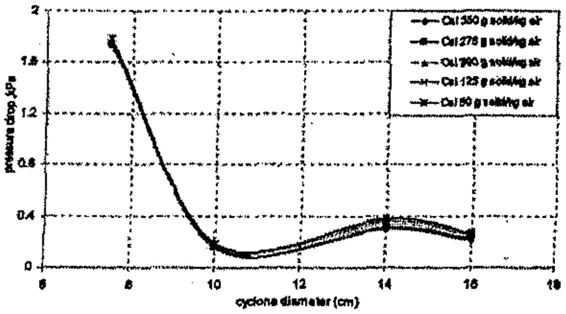

Fig.6. Variation of pressure drop with cyclone diameter for particle size (510μm) with different solid loading at constant inlet velocity of 10.3m/s.

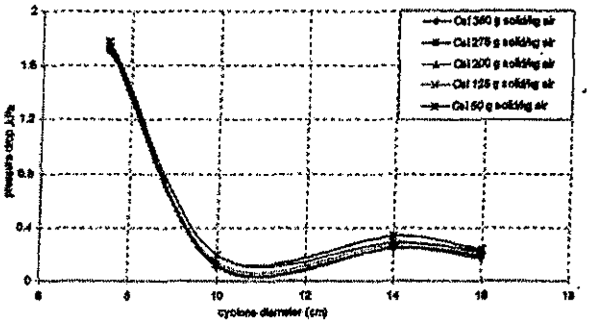

Fig.7. Variation of pressure drop with cyclone diameter for particle size (sand overall) with different solid loading at constant inlet velocity of 10.3m/s.

This characteristics can be attributed to, as the cyclone size increased at constant inlet velocity, the rectangular inlet area, the outlet tube area and the total area of the contact surfaces between air flow and the cyclone wall (the sum of the top cover area and the cyclone barrel and cone area) become larger. Pressure losses are mainly occurred at the walls of the cyclone swirling loss and outlet tube (dissipation loss of air dynamic energy). The increase of area have an effect on the pressure drop due to the variation of velocity and hydraulic diameter inside the cyclone which decrease the Reynolds number and leads to decrease wall friction coefficient results in decreased losses in the separation space. However at the same time, the decrease in the magnitude of the tangential velocity leads to decreased losses in the vortex finder. The decreasing of pressure drop with increasing cyclone size is in agreement with the published data EL – Batsh, et al. [7].

3.2. Effect of Particle Size on the Pressure Drop

Figs. 8 to 11 represent the cyclone pressure drop at different particle sizes and various dust loadings at constant mean inlet velocity of cyclones. It is shown from these Figures that the cyclone pressure drop increases with increasing the particle size. The general trends of pressure drop at various particle size curves are that the pressure drop increases sharply with increasing the particle size from 70 to 225μm and then increases gradually at a low slope with increasing the particle size from 225 to 510μm. It is clear from the results that there is no unique trend of the variation of pressure drop with particle size. In general increasing particle size will increase the centrifugal force.

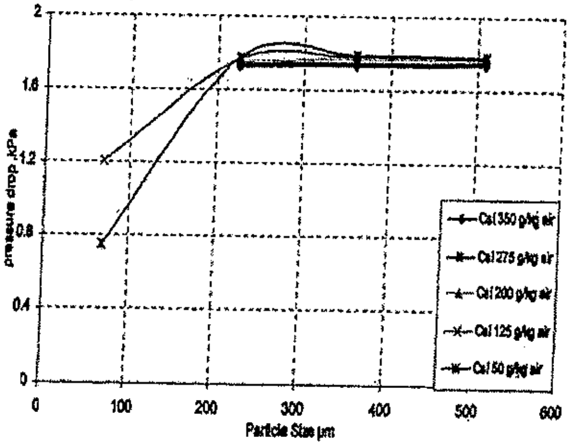

Fig. 8 Variation of pressure drop with particle size for cyclone diameter (7.5 cm) with different solid loading at constant inlet velocity of 10.28m/s.

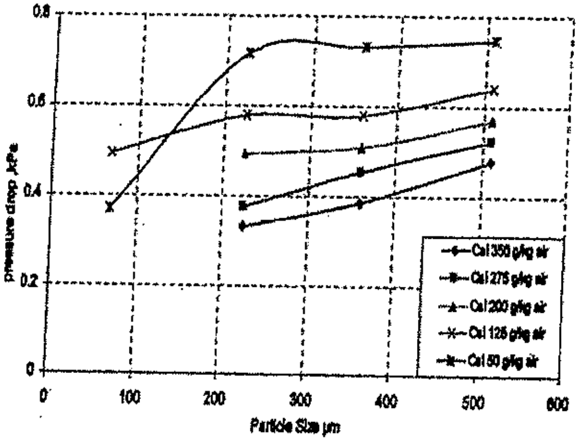

Fig. 9 Variation of pressure drop with particle size for cyclone diameter (10 cm) with different solid loading at constant inlet velocity of 17.66 m/s.

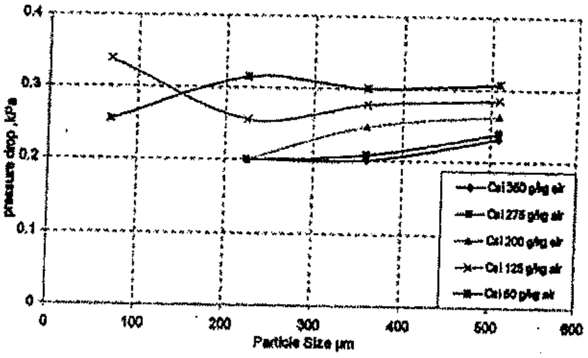

Fig. 10 Variation of pressure drop with particle size for cyclone diameter (14 cm) with different solid loading at constant inlet velocity of 9.48 m/s.

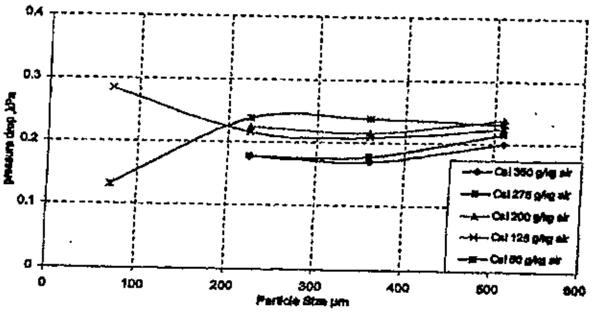

Fig. 11 Variation of pressure drop with particle size for cyclone diameter (16 cm) with different solid loading at constant inlet velocity of 9.94 m/s.

3.3. Effect of Inlet Velocity on the Pressure Drop

The effect of inlet velocity on cyclone pressure drop at various particle sizes and different dust loading for all cyclone used, is shown in figs. 12 to 19. These figures indicate that for all test conditions, the pressure drop depends strongly on the mean inlet velocity. The general trends of the pressure drop are that, it increases gradually with increasing the inlet velocity up to 9.2 m/s and then increases with higher rate with increasing the inlet velocity. This can be attributed to that the average inlet velocity reflects different effects in different flow regimes of the air – cyclone wall interaction.

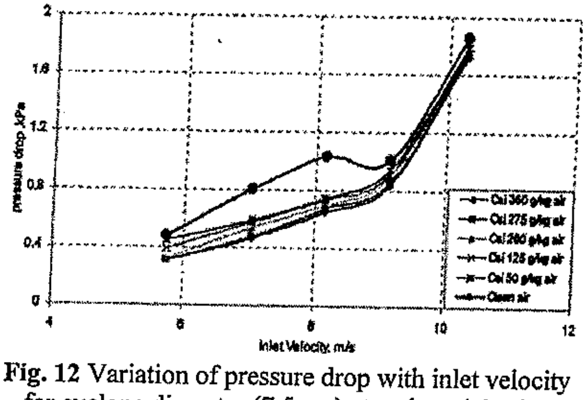

Fig. 12 Variation of pressure drop with inlet velocity for cyclone diameter (7.5 cm) at and particle size (360μm) with different solid loading.

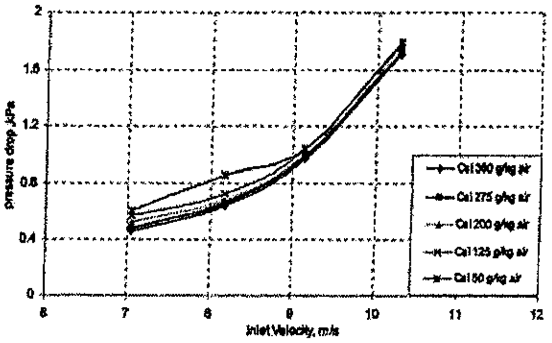

Fig. 13 Variation of pressure drop with inlet velocity for cyclone diameter (7.5 cm) at and particle size (sand overall) with different solid loading.

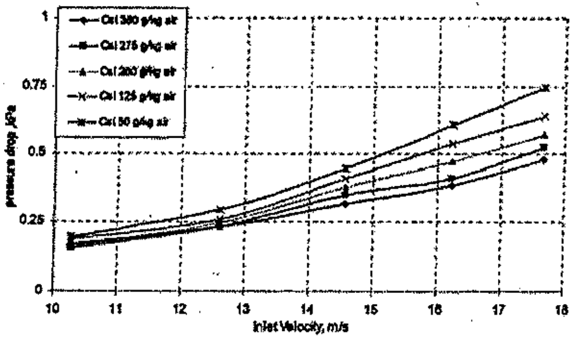

Fig. 14 Variation of pressure drop with inlet velocity for cyclone diameter (10 cm) at and particle size (510µm) with different solid loading.

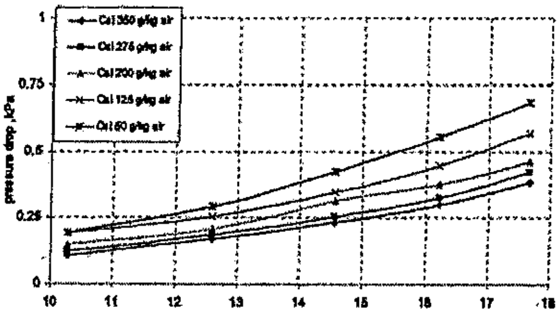

Fig. 15 Variation of pressure drop with inlet velocity for cyclone diameter (10 cm) at and particle size (sand overall) with different solid loading.

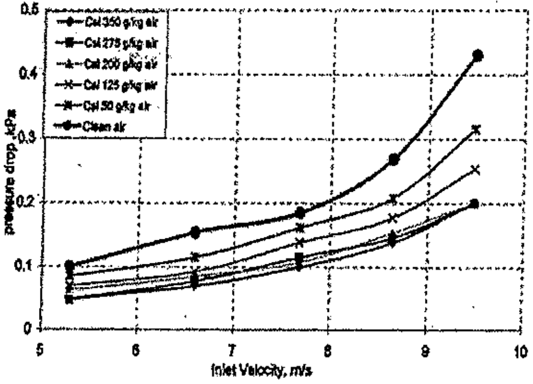

Fig. 16 Variation of pressure drop with inlet velocity for cyclone diameter (14 cm) at and particle size (225µm) with different solid loading.

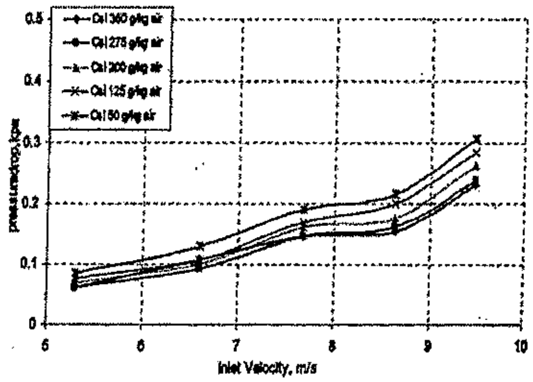

Fig. 17 Variation of pressure drop with inlet velocity for cyclone diameter (14 cm) at and particle size (510µm) with different solid loading.

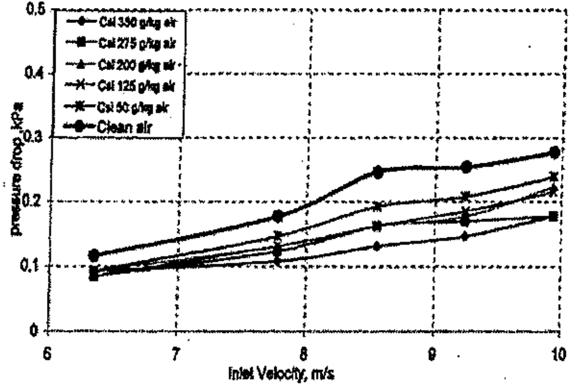

Fig. 18 Variation of pressure drop with inlet velocity for cyclone diameter (16 cm) at and particle size (225µm) with different solid loading.

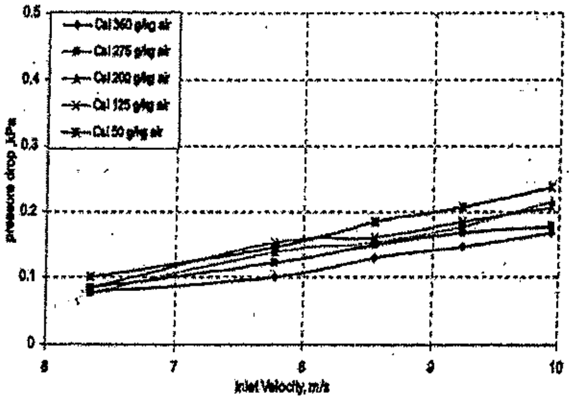

Fig. 19 Variation of pressure drop with inlet velocity for cyclone diameter (16 cm) at and particle size (360µm) with different solid loading.

Pressure losses in cyclones are dominated by viscous dissipation of this quantity in the vortex finder. Such dissipation is roughly proportional to the absolute magnitude of squared tangential velocity (V_t^2), so that any influence that tends to increase the strength of the vortex increases the losses. As the inlet velocity increases the tangential velocity increases, results in an increase in the swirling loss which increases the pressure drop. Similar trend of the effect of inlet velocity on the pressure drop was reported by De, et al. [2], EL – Batsh, et al. [7] and Chen, et al. [8].

3.4. Relation between Clean Air and Dusty Air Pressure Drop

Since the pressure drop is one of the important performance parameters of the cyclone separators, knowledge of the pressure drop is very important for the cyclone designers and user, for proper design and safe operation. Many researchers have developed different procedures to estimate the pressure of cyclone. Most of the procedures however are suitable only for pure gases, and not very satisfactory in generality. Moreover, the pressure drop of a cyclone under the condition of dusty gases is of importance, and it is much different from that under the condition of pure gases. Nevertheless, the reduction of the pressure drop over a cyclone dealing with dusty gases has not been solved. Therefore, there is clearly a need for reliable data on the variation of dust gases pressure drop at various operating geometrical conditions with a view to develop possible relationships between the clean – gas and the dusty – gas pressure drop . This will be very convenient for practical purpose. To achieve this purpose the extensive series of experiments of the clean – air and dusty - air pressure drop at various operating conditions and cyclone sizes of the present work will be used. In analyzing the results of pressure drop tests, the relationship illustrated in fig. (20), was obtained from the experiments results between the clean – air and dusty – air pressure drop were examined and is independent of the cyclone size. Nevertheless, it is dependent of the particle size, dust loading and inlet velocity .This Figure indicates that there is a very good relation between $\Delta P_{s.d}$ and $\Delta P_{s.c}$ for all the data. Equation for the regression curve was derived from figure (20) using the method of least square. The relation could be defined by the following approximate relation:

$$\Delta P_{s.d} = 1.452\left[\frac{\Delta P_{s.c}^{\;1.2}}{C_{si}^{\;0.122}}\right]$$

The correlation coefficient for the relationship is 0.9375. These finding is the interesting feature of this correlation. This would seem to be a most useful tool in the prediction of the pressure drop for dusty – air.

4. CONCLUSION

Based on the results obtained from the present extensive experimental investigation, the following broad conclusion can be obtained:

1. The pressure drop across the cyclone decreased with increasing the cyclone size. This decrease was sharp with increasing the size from 7.5 cm to 10 cm.
2. The pressure drop increases sharply with increasing the particle size up to 225μm and then increased gradually at a low slop with increasing the particle size from 225 to 510μm.
3. The pressure drop increased gradually with increasing the inlet velocity up to 9.2 m/s and then increased sharply with increasing the inlet velocity.
4. The pressure drop for dusty air well correlated with the pressure drop for clean air directly which was independent of the cyclone size, inlet velocity and particle size. This relation could be defined by the following approximate relation:

$$\Delta P_{s.d} = 1.452\left[\frac{\Delta P_{s.c}^{\;1.2}}{C_{si}^{\;0.122}}\right] .$$

Thus, the correlation reported not previously addressed here is very interesting and represents an addition to knowledge of this aspect which could lead to the prediction of the actual pressure drop of dusty gases from tests on clean gases as are easy to conduct.

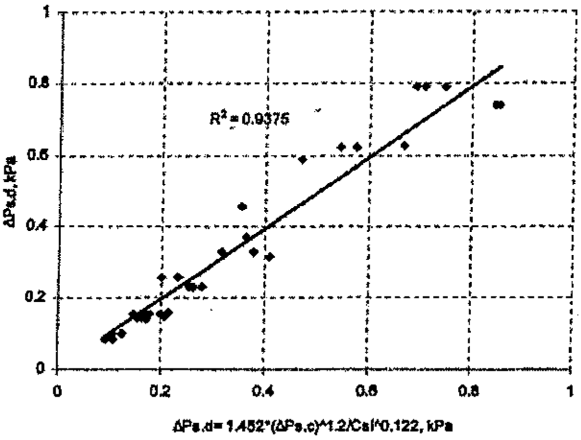

Fig. 20. Relation between pressure drop for clean air and pressure drop for dusty air in cyclone separator.

5. REFERENCES

[1] Biffin, M., Syred, N., and Sage, P., 1984,"Enhanced Collection Efficiency for Cyclone Dust Separators", Chem. Eng., Vol. 62, PP. 261 – 265.

[2] De, S., Lal, A. K., and Nag, P. K., 1999,"An Experimental Investigation on Pressure Drop and Collection Efficiency of Simple Plate – Type Impact Separator", Powder Technology 106-1999, PP. 192-198.

[3] Gil, A., Luis, M., and, Cortes, C., 1999,"Effect of the Solid Loading .on the Performance of a Cyclone with Bottom Pneumatic Extraction of Solids", Zaragoza 3.50015, PP. 1-24.

[4] Fassani, F. L., and Goldstein, L., 2000,"A Study of the Effect of High Inlet Solids Loading on a

Cyclone Separator Pressure Drop and Collection Efficiency", Powder Technology 107, PP., 60-65.

[5] Avci, A., and Karagoz, I., 2001,"Theoretical Investigation of Pressure Losses in Cyclone Separators", Int., Comm., Heat Mass Transfer,Vol. 28 , No.1, PP. 107-117.

[6] Shin, M. S., kim, H. S., Jang, D.S., Chung, J.D., and Bohnet, M., 2005,"A numerical and Experimental Study on a High Efficiency Cyclone Dust Separator for High Temperature and Pressurized Environments", Applied Thermal Engineering 25, PP. 1821 – 1835.

[7] EL – Batsh, H., Abd – Hamied, A. A., and Hamed, M. H., 2006, "Numerical and Experimental Study of the Flow Field and Particle Separation Through Cyclone Separator", Energy: Production, Distribution, and Conservation, Vol. 2, PP. 963 - 972.

[8] Chen, J., Lu, X., Liu, H., and Yang, C., 2006,"Effect of the Bottom Contracted and Edge – Sloped Vent – Pipe on the Cyclone Separator Performance", Chemical Engineering Journal, PP. 1 – 6.

[9] Chen, J., and Shi, M., 2007, "A Universal Model to Calculate Cyclone Pressure Drop", Powder Technology 171, PP.184 – 191.

6. NOMENCLATURE

A = flow area (m^2)
C_{si} = solid loading (g_{solids}/kg_{air})
D = cyclone diameter,7.5,10,14 and 16cm
M_{si} = solid mass (g)
M_a= air mass flow rate (kg)
P_{si} = static pressure at cyclone inlet (kPa)
P_{so} = static pressure at cyclone outlet (kPa)
Q = volumetric flow rate of air at inlet (m^3/s)
V_i = inlet velocity of air (m/s)
$\Delta P_{s.d}$ = pressure drop for dusty air
$\Delta P_{s.c}$ = pressure for clean air