DEVELOPMENT AND VALIDATION OF NEW EQUATIONS FOR PREDICTION OF THE PERFORMANCE OF TANGENTIAL CYCLONES

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Abstract New equations have been developed to predict the effect of geometrical dimensions of tangential cyclones on their operational performances. To check the validity of the derived equations, an experimental apparatus was set up and some experimental work was performed. It was observed that the experimental results confirm properly the theoretical predictions.

Key Words Cut Size, Velocity Head, Pressure Drop, Collection Efficiency, Geometry Parameter

چکیده معادلات جدیدی برای بررسی تاثیر ابعاد هندسی بر عملکرد سیکلون های مماسی تدوین گردید. برای حصول اطمینان از درستی معادلات تدوین شده دستگاهی طراحی و آزمایشهای لازم انجام شد. پس از انجام آزمایشها مشاهده شد که معادلات تدوین شده از دقت لازم برخوردارند و با نتایج تجربی سازگاری کامل دارند.

1. INTRODUCTION

Cyclones are the most widely used equipments for separating industrial dusts from air or process gasses. Ease of construction, low cost, ability of operation at sever conditions and good mechanical stability have been the reasons for cyclones popularity and their wide usage in industry.

Cyclones are designed in different types. Among them, reverse flow cyclones are the most common ones. In these cyclones, the dust-laden gas stream enters the top section of the cylindrical body tangentially. Tangential entry imparts a spinning motion to the gas-dust mixture, whereupon the gas and the suspended particles are thrown toward the wall of the cylinder. Spiraling gas imparts some inward radial acceleration to the particle, which at the same time gains downward acceleration due to gravitational force acting on it. The particles continue to descend in a spiraling path down the wall while the gas, freed of solids moves upward in the central core and leaves the cyclone through the gas outlet tube at the top. This tube is a cylindrical sleeve, whose lower end extends below the level of the feed port. Figure 1 shows a tangential cyclone.

Design of cyclones for efficient separation of gas – solid mixtures, has been the subject of many investigations. Stairmand [1], Strauss [2], Koch and Licht [3] and others have given guidelines for designing cyclones. To design a cyclone as efficient as possible, it is necessary to know how the cyclone's geometrical dimensions, affect on its operational performances. Developing the equations that clearly show the effect of feed and cyclone parameters on the performance is somewhat difficult. This is due to the fact that many parameters are interdependent.

This paper analyses parts of the work of the previous investigators to identify the interdependent parameters and to get a deeper knowledge about their characteristics. Resolution of the subject may help to derive better equations for design purposes. With this idea in mind, new equations have been derived, which will be introduced in the paper and it will be shown how the cyclone dimensions can affect on its practical performance.

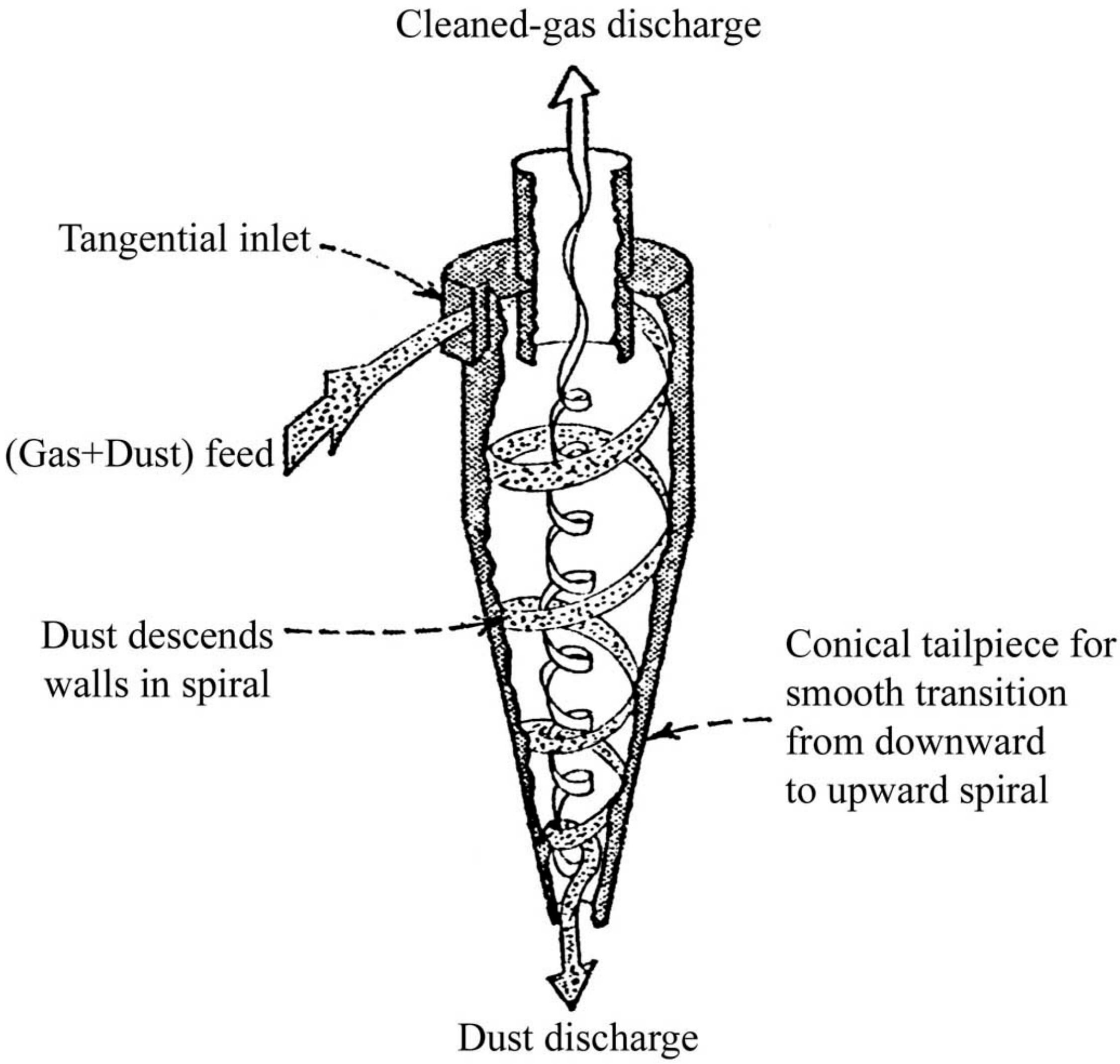

Figure 1. Tangential cyclone removes dust from gas.

2. CUT SIZE

Many theories have been proposed to predict the performance of a cyclone. In some of these theories attempts have been made to predict the critical particle diameter D_{pc}. This is the size of the smallest particle that is theoretically separated from the gas stream. Rosin, Rammler and Intelmann [4] assumed that those particles whose radial velocity were equal to their terminal settling velocity and could reach to the cyclone's wall (during their residence time in the cyclone), were the smallest particles that could be separated from the gas stream. Based on this assumption, they derived the following formula:

$$D_{pc}=\sqrt{\frac{9\mu b}{\pi N v_i(\rho_p-\rho)}} \tag{1}$$

where in the above formula, b was the cyclone inlet port width, v_i, the feed inlet velocity to the cyclone, μ and ρ the gas viscosity and gas density, ρ_p the particle density and N the number of turns of feed stream within the cyclone body.

The drawbacks of Equation 1 are as follows:

1. It assumes a fractional separation efficiency of 0% for particles with a size smaller than D_{pc} and a fractional separation efficiency of 100% for particles bigger than D_{pc}. While in practice, such a sharp change is not observed.
2. *N* in the equation is an unknown parameter and has not been defined clearly. For cyclones proportional in dimensions to that which was used by Rosin-Rammler, *N* is recommended to be equal to 5. For other cyclones *N* still remains unknown.

Lapple [5] corrected the Rosin-Rammler assumptions by the following discussion:

Particles smaller than D_{pc}, can also be separated from the gas-dust mixture if their distances from the cylindrical body of the cyclones is less than b. He assumed an efficiency of separation of 50% for particles at b/2 from the cyclone wall an defined the following formula for prediction of their diameters:

$$D_{p50\%}=\sqrt{\frac{9\mu b}{2\pi N v_i(\rho_p-\rho)}} \tag{2}$$

This line of reasoning improved the shape of the graph of fractional efficiency versus particles' diameters and made it to be better consistent with practical observation. Lapple did not propose any relation for calculation of N.

F.A. Zenz and B. Kallen [6] altered Equation 2. In their experiments, they observed that N was not a fixed parameter and changed with gas flow rate and particle's concentrations. The variation of N with experimental conditions influenced on the size of D_{pc}. Therefore they defined a correction factor λ and introduced the following formula:

$$D_{pc}=\sqrt{\frac{9\mu b}{\lambda\pi N v_i(\rho_p-\rho)}} \tag{3}$$

In Equation 3 *N* still was undefined for the cyclones which were not proportional in dimensions to that which was used by Rosin et. al. λ was hard to be analytically identified. They derived an empirical correlation for prediction of λ which related it to the feed inlet velocity v_i, particle's density ρ_p and void spaces within the cyclone volume €. This correlation is somewhat difficult and impractical in use, because it is hard to measure € when particles present at different concentrations in the feed.

Wallas [7] defined the critical diameter by:

$$D_{pc}=\sqrt{\frac{9\mu b}{4\pi N v_i(\rho_p-\rho)}} \tag{4}$$

and N by:

$$N = v_i\left[0.1079-0.00077v_i+1.924\times10^{-6}v_i^2\right] \tag{5}$$

where v_i was the feed inlet velocity to the cyclone in ft/s.

3. MODIFICATION OF THE PREVIOUS WORK

Our experiments confirmed that N was not a constant parameter and it varied as feed concentration was changed. We also believed that N must be a strong function of cyclone geometrical dimensions.

With this idea in mind, we started from basic principles and derived the following formula:

$$N=\left(\frac{D_C^2L_1-D_e^2S}{4A_iD_C}\right)\left(\frac{L_2D_C}{L_1\bar{D}\sin^2\beta}+1\right)\left(\frac{C_P}{C_i}\right) \tag{6}$$

where in Equation 6, C_i is the particles' concentration in the inlet feed, C_p the particles' concentration within the cyclone volume, D_c, D_e, L_1, L_2, S and A_i are cyclone geometrical dimensions as shown in Figure 2. $\bar{D}$ is the equivalent cylindrical diameter of the conical section of the cyclone and β is the angle of inclination of the conical body of the cyclone with

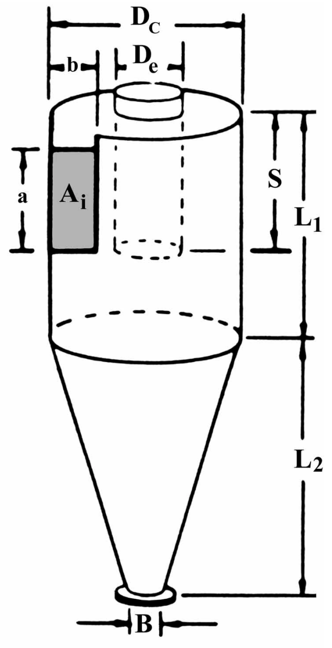

Figure 2. The cyclone geometrical dimensions.

respect to horizone. $\overline{D}$ was found to be:

$$\bar{D} = \frac{D_c - B}{\ln(D_c / B)} \tag{7}$$

where in the above equation, B is the discharge diameter of the cyclone for solid particles.

Analysis of Equation 6 reveals that any change in the cyclones' dimensions that would result in a higher N, will increase the separation efficiency. When the feed (dust and gas) mixture is very lean, then it can be assumed that the gas to the cyclone is clean and for the clean gas we can write:

$$N_{clean} = \left(\frac{D_c^2 L_1 - D_e^2 S}{4 A_i D_C}\right)\left(\frac{L_2 D_C}{L_1 D \sin^2\beta} + 1\right) \tag{8}$$

Combining Equations 8 and 6, leads to:

$$N = N_{clean} \cdot \frac{C_p}{C_i} = \lambda N_{clean} \tag{9}$$

It seems that the correction factor λ that was proposed by F.A. Zenz and B. Kallen for use in the Rosin-Rammbler equation is just the ratio of particles' concentration within the cyclone volume to the particles' concentration in the inlet feed. Detailed analysis of λ shows that it is the ratio of particles average residence time to the average residence time of the clean gas.

It is analytically hard to determine C_p, because it is the particles' holdup in the unit volume of the cyclone and it's value depends on the dynamic behavior of the system. The easiest way to determine λ is to count the number of particles revolutions within a cyclone N and dividing it by N_{clean} which is determined by Equation 8. For very lean mixtures λ is approximately equal to 1 and N can be determined from Equation 8 for use in Equation 1 or 2.

4. PRESSURE DROP

Pressure drop in a tangential cyclone, is described by the difference between the feed pressure at the cyclone's inlet pipe and the clean gas pressure at the cyclone's exit pipe.

Several expressions have been developed to predict cyclone pressure drop [8-10,11] (see Table 1). These expressions vary greatly in complexity and in the degree to which they rely on empiricism rather than theory. All can be used to calculate cyclone pressure drop as the number of gas inlet velocity head ΔH, which is then converted to static pressure loss, in inch of water by:

$$\Delta P = (0.003 \rho_G V_i^2)(\Delta H) \tag{10}$$

Most of the expressions for ΔH that are seen in Table 1 were published before 1950; little theoretical work on cyclone pressure drop has been done since. Due to the empirical nature of these relations, predicted ΔH values sometimes differ from measured values by more than a factor of two.

While the discussion of pressure drop theories above applies to clean gas, cyclone pressure drop decreases as dust concentration increases. Briggs [12] has presented an empirical expression to calculate the reduction in pressure drop due to the dust loading (in g/m^3) if the clean gas pressure drop is known:

$$\Delta P_{dusty} = \frac{\Delta P_{clean}}{(1 + 0.0086\sqrt{C_i})} \tag{11}$$

TABLE 1. Equations for Predicting Pressure Drop as the Number of Inlet Velocity Heads, ΔH .

Source	Equation
Shepherd and Lapple [8]	$\Delta H = \frac{16ab}{D_e^2}$
First [9]	$\Delta H = \frac{24ab}{D_e^2}\left[\frac{D_C^2}{L_1 L_2}\right]^{\frac{1}{3}}$
Stairmand [10]	$\Delta H = 1 + 2\ {}^{2}\left(\frac{2(D_C - b)}{D_e} - 1\right) + 2\left(\frac{4ab}{\pi D_e^2}\right)$ $\varphi = \frac{\sqrt{\frac{D_e}{2(D_C - b)} + \frac{4GA}{ab}} - \sqrt{\frac{D_e}{2(D_C - b)}}}{\frac{2GA}{ab}}$ $A = \frac{\pi}{4}(D_C^2 - D_e^2) + \pi D_C L_1 + \pi D_e S + \frac{\pi}{2}(D_C + B)\left[\left(\frac{D_C - B}{2}\right)^2 + L_2^2\right]^{\frac{1}{2}}$ **G is a friction factor with a value of 0.005.**
Alexander [11]	$\Delta H = 4.62\left(\frac{ab}{D_C D_e}\right)\left[\left\{\left(\frac{D_C}{D_e}\right)^{2n} - 1\right\}\left(\frac{1-n}{n}\right) + f\left(\frac{D_C}{D_e}\right)^{2n}\right]$ $f = 0.8\left[\frac{1}{n(n-1)}\left(\frac{4 - 2^{2n}}{3}\right) - \left(\frac{1-n}{n}\right)\right] + 0.2\left[\left(\frac{1-n}{n}\right)\left(2^{2n} - 1\right) + 1.5\left(2^{2n}\right)\right.$

5. A NEW EQUATION FOR PRESSURE DROP MEASUREMENTS

Starting from Darcy's equation and modifying it for a spiraling flow within the cylindrical section of a cyclone led to the following equation:

$$\Delta P_1 = f\rho_G V^2\left[\frac{2\pi R_c N_1}{(R_c - R_e)\cos^3\alpha}\right] \quad (12)$$

where in the above equation N_1, is the number of turns of flow stream on the cylindrical wall of the cyclone and is given by:

$$N_1 = \frac{D_c^2 L_1 - D_e^2 S}{4 A_i D_c} \tag{13}$$

α, in Equation 12, is the angle at which the flow stream spirals down on the cylindrical wall of the cyclone. It is found from:

$$\tan\ \alpha = \frac{L_1}{2\pi R_c N_1} \tag{14}$$

In a similar way, pressure drop inside the conical section of the cyclone was found to be:

$$\Delta P_2 = f' \rho_G V^2 \left[\frac{2\pi \bar{R} N_2}{(R_c - R_e)\cos^3 \alpha'} \right] \tag{15}$$

where in equation 15, $\bar{R}, \alpha'$ and N_2 are determined from:

$$\bar{R} = \frac{1}{2} \bar{D} \tag{16}$$

$$\tan \alpha' = (\tan \alpha)(\sin \beta) \tag{17}$$

$$N_2 = \frac{L_2}{2\pi \bar{R} \tan \alpha' \sin \beta} \tag{18}$$

In the central part of the cyclone, flow spirals up and its pressure drop is determined by:

$$\Delta P_3 = f'' \rho_G V_i^2 \left[\frac{2\pi R_e (N_1 + N_2)}{R_e \cos^3 \alpha''} \right] \tag{19}$$

α'' in the above formula is the angle at which flow spirals up and moves toward the cyclone exit pipe. It is found by:

$$\tan\ \alpha'' = \frac{(L_1 + L_2)}{2\pi R_e (N_1 + N_2)} \tag{20}$$

Total pressure drop within the cyclone body, was assumed to be the sum of $\Delta P_1, \Delta P_2$ and ΔP_3. Then by the assumption that the fanning friction factors f, f' and f'' were the same for the turbulent flow inside the cyclone, the total pressure drop formula was found to be:

$$\Delta P = (\frac{2\pi f}{0.003})(0.003 \rho_G V_i^2) \left[\frac{R_c N_1}{(R_c - R_e)\cos^3 \alpha} + \frac{\bar{R} N_2}{(R_c - R_e)\cos^3 \alpha'} + \frac{N_1 + N_2}{\cos^3 \alpha''} \right]$$

or

$$\Delta P = K.(0.003 \rho_G V_i^2)(\Delta H) \tag{21}$$

Applying experimental measurements, operational conditions and geometrical dimensions in equation 20, led to the determination of K to be very close to 1.0, for all experiments. This finding permitted us to define a new equation for ΔH, which is:

$$\Delta H = \frac{R_c N_1}{(R_c - R_e)\cos^3 \alpha} + \frac{\bar{R}' N_2}{(R_c - R_e)\cos^3 \alpha'} + \frac{N_1 + N_2}{\cos^3 \alpha''} \tag{22}$$

Equation 22 determines the number of velocity heads for a clean gas. If $N_1, N_2, \alpha, \alpha'$ and α'' were available for the system it can be used for calculating of number of velocity heads of a gas-solid feed mixture too.

6. COLLECTION EFFICIENCY

Collection efficiency η is defined as the fraction of particles of any given size that is retained by the cyclone. Many theories have been used to predict the cyclone efficiency. Of these theories the one by Leith and Licht [13] has been most commonly used. Leith and Licht assumed that radial acceleration and radial gas velocity in the cyclone can be neglected. Their model accounts for turbulent gas flow by assuming that at any height in the cyclone, uncollected dust is completely and uniformly mixed. An average residence time for

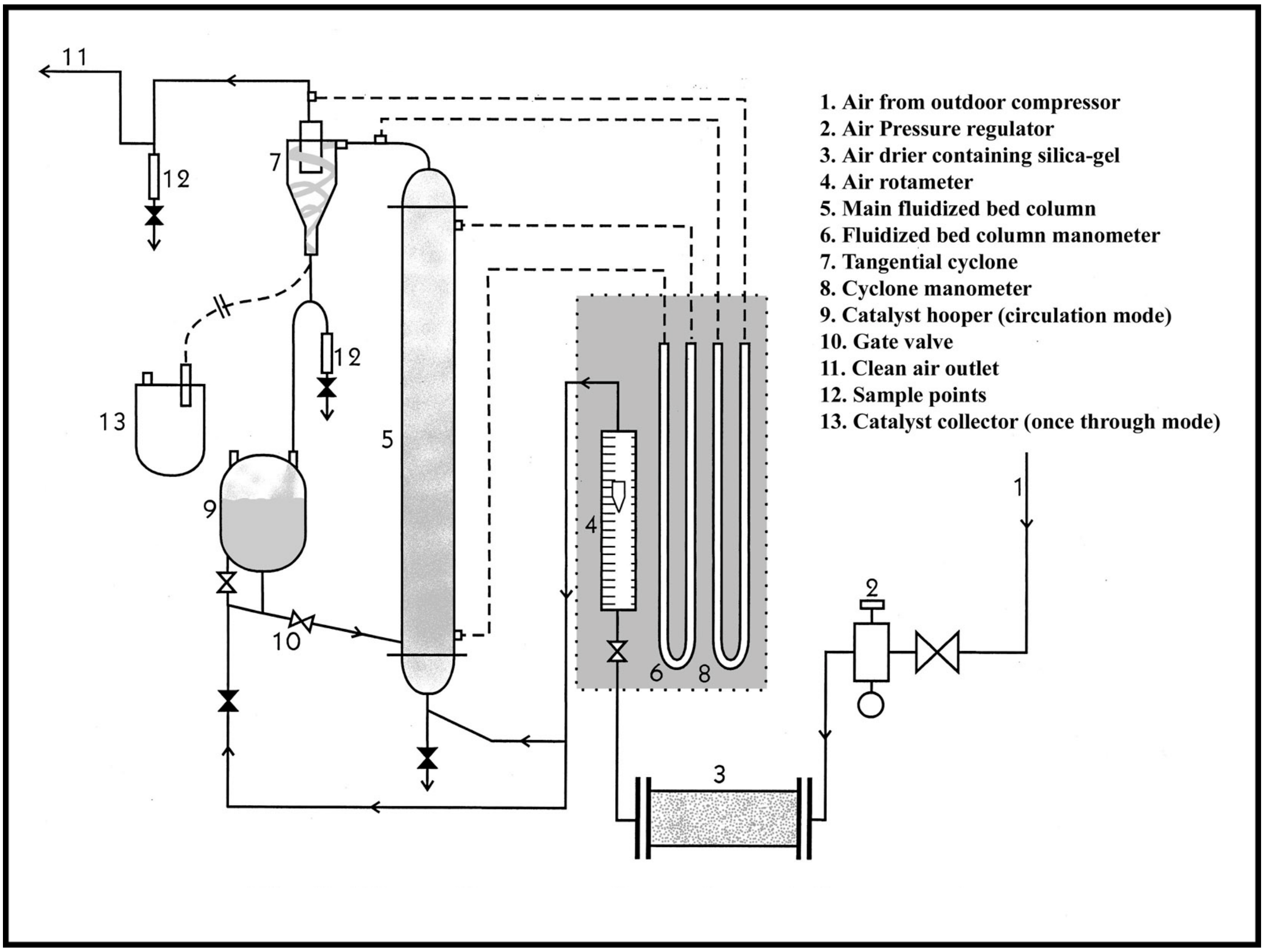

Figure 3. Flow diagram of experimental apparatus.

gas in the cyclone is determine from cyclone dimensions and gas throughput. The resultant expression for collection efficiency is:

$$\eta = 1 - \exp\left[-2(C\Psi)^{\frac{1}{2n+2}}\right] \tag{23}$$

where n is given by Alexander [11] as:

$$n = 1 - \left[(1 - 0.67 D_c^{0.14})(T/283)^{0.3}\right] \tag{24}$$

In Equation 24, cyclone diameter must be expressed in meters and gas temperature in $^{\circ}K$.

The influences of particle and gas properties are combined in Ψ, a modified inertia parameter:

$$\Psi = \frac{\rho_p d_p^2 V_i (n+1)}{18 \mu D_c} \tag{25}$$

The term C in Equation 23 is a dimensionless geometry parameter that depends only on the eight-cyclone dimension ratio. For any cyclone design C is a constant; each design has a unique value of C. A cyclone with a higher value of the geometry parameter C will be more efficient than one with a lower C for all operating conditions. Appendix I shows the equation for calculation of C.

7. MODIFICATION OF THE EQUATION FOR COLLECTION EFFICIENCY

As appendix I shows the equation for calculation of C is lengthy and tedious. Moreover, it is not clear how this lengthy expression is derived. The assumption of an average residence time for gas (which was pointed to in derivation of Equation 23) is objectionable too, because it is more acceptable to use the average residence time of solid particles instead of that for clean gas in the equation. This modifies the equation as shown below:

$$\eta = 1 - \exp\left[-2(\lambda C \psi)^{\frac{1}{2n+2}}\right] \qquad (26)$$

It is further suggested to use the dimensionless parameter ΔH, as defined by Equation 22, instead of C in Equation 26. The reasons that support this suggestion are as follows:

1. ΔH, For a clean gas is a pure function of the geometrical dimensions of cyclone.
2. It ties a relation between cyclone pressure drop and the cyclone efficiency.
3. For a given design, a cyclone with a higher value of ΔH will be more efficient than one with a lower ΔH for all operating conditions. In practice, it has been observed that when the efficiency of a given cyclone is increased, its presure drop is increased too.

8. EXPERIMENTAL APPARATUS

To verify the derived equations, an experimental apparatus was set up and some experimental work were carried out. Figure 3 shows the flow diagram of the apparatus, which was employed for the experiments.

Air from an outdoor compressor was routed through line 1 to pressure regulating device 2, and dried in vessel 3 by a bed of silica gel particles. Then it was directed from vessel 3 to main column 5, while its flow rate was controlled by flow meter 4. Zeolite catalyst from vessel 9 was discharged into the main column 5 via the gate valve 10. Gate valve 10 and flow meter 4 enabled to determine the solid to air ratio when the experiment was being down in once through mode operation. The main column 5, was a Pyrex tube with an inside diameter of 93 mm and a length of 1220 mm. The fluidization of catalyst by air was performed in this column. Gas and solid leaving the top of the column were routed to the tangential cyclone 7, where the solid particles were separated from the gas stream and discharged either into vessel 13 (once through mode operation), or in vessel 9 for catalyst recirculation. Sample points 12 and 14 enabled one to sample catalyst particles from the bottom and top streams of the cyclone.

Manometers 6 and 8 were available to measure pressure drop through the fluidized bed and across the T/G cyclone. The geometries of cyclone 7, which was used in the experiment, are shown in Appendix I.

9. EXPERIMENTAL RESULTS AND DISCUSSION

A. Clean Gas Pressure Drop Using clean air and with no catalyst in the system, experiments were carried out and clean air pressure drop inside the tangential cyclone was measured. The results are shown in Table 2. Then the experimental measurements were compared with the theoretical predictions of the previous investigators and with those predicted from our proposed equations (Equation 22 and 10). Table 3 shows the result. As are seen in the table, our proposed equations are confirmed by experiments and are reliable enough for pressure drop measurements. Figures 4 through 8 compare the experimental results with the theoretical predictions graphically.

B. The λ Parameter Measurements The parameter λ was measured experimentally at different catalyst to gas ratios. In experiments 14 to 17, gas rate was altered and catalyst addition rate was retained constant. In experiments 17 to 20, catalyst addition rate was altered and gas rate to the cyclone was retained constant. Photos from each experiment were taken and the number of turns of spiraling flow within the cyclone was counted. Then using Equations 8 and 9,for each experimental conditions, λ were determined and the results were tabulated in Table 4.

Figure 9 shows the variation of λ with catalyst

TABLE 2. Clean Air Pressure Drop Results in the Tangential Cyclone.

Air flow rate (m^3/hr)	V_I (m/s)	ΔP ΔP mm-H_2O	Air flow rate (ft^3/hr)	V_i (ft/s)	ΔP ΔP Inch-H_2O
12.52	1.61	4.0	442.1	5.26	0.157
18.78	2.42	6.0	663.2	7.92	0.236
25.04	3.22	10.0	884.2	10.56	0.394
31.30	4.03	15.0	1105.3	13.20	0.591
37.56	4.83	21.0	1326.3	15.84	0.827
43.82	5.64	29.0	1547.4	18.48	1.142
50.08	6.44	41.0	1768.4	21.12	1.614
56.34	7.25	52.0	1989.5	23.76	2.047

TABLE 3. Comparison of the Experimental Pressure Drop Results with the Predictions from the Work of the Previous Investigators and from our Proposed Equations.

Air flow rate (m^3/hr)	V_i (m/s)	Shepherd Equation mm-H_2O	First Equation mm-H_2O	Stairmand Equation mm-H_2O	Alexander Equation mm-H_2O	Proposed Equation mm-H_2O	Experimental Results mm-H_2O
12.52	1.61	3.7	5.1	1.4	2.8	2.4	4.0
18.78	2.42	8.3	11.5	3.1	6.2	5.8	6.0
25.04	3.22	14.8	20.4	5.5	11.1	9.7	10.0
31.30	4.03	23.2	31.9	8.7	16.2	15.0	15.0
37.56	4.83	33.3	45.9	12.5	25.0	21.7	21.0
43.82	5.64	45.4	62.4	17.0	34.0	29.5	29.0
50.08	6.44	59.3	81.6	22.2	44.4	38.5	41.0
56.34	7.25	74.9	103.2	28.1	56.2	49.0	52.0

to gas ratio. As is seen in the figure λ decreases as catalyst to gas ratio is increased. This means that the number of turns in the cyclone (N_{dusty}) decreases with increasing catalyst concentrations. Figures 10 and 11 show the photos of the cyclone at the conditions of experiments of 14 through 20.

C. Gas-Solid Mixture Pressure Drop

Pressure drop measurements were carried out in experiment 14 through 20, for different catalyst to gas ratios. It was observed that as catalyst to gas ratio was increased, the pressure drop within the cyclone was decreased. Predictions from Briggs' equation and Equations 22 and 10 were compared with the experimental measurements. The results are shown in Table 5. As is seen in the table, predictions from our proposed formula (Equations 22 and 10) are consistent with experimental measurements. This finding again dictates the validity of our proposed formula. The decrease of pressure drop within the cyclone with catalyst concentration seems to be due to the decrease of number of turns of flow inside the cyclone with catalyst concentration. When gas feed rate to the cyclone is constant, its average residence time within the cyclone is constant too. As catalyst to gas ratio is increased, the average residence time of catalyst particles within the cyclone is decreased. This causes λ, which is the ratio of solid's residence time to gas residence time to be decreased. Reduction of λ reduces the number of turns in the cyclone, which consequently causes the pressure drop inside the cyclone to be decreased.

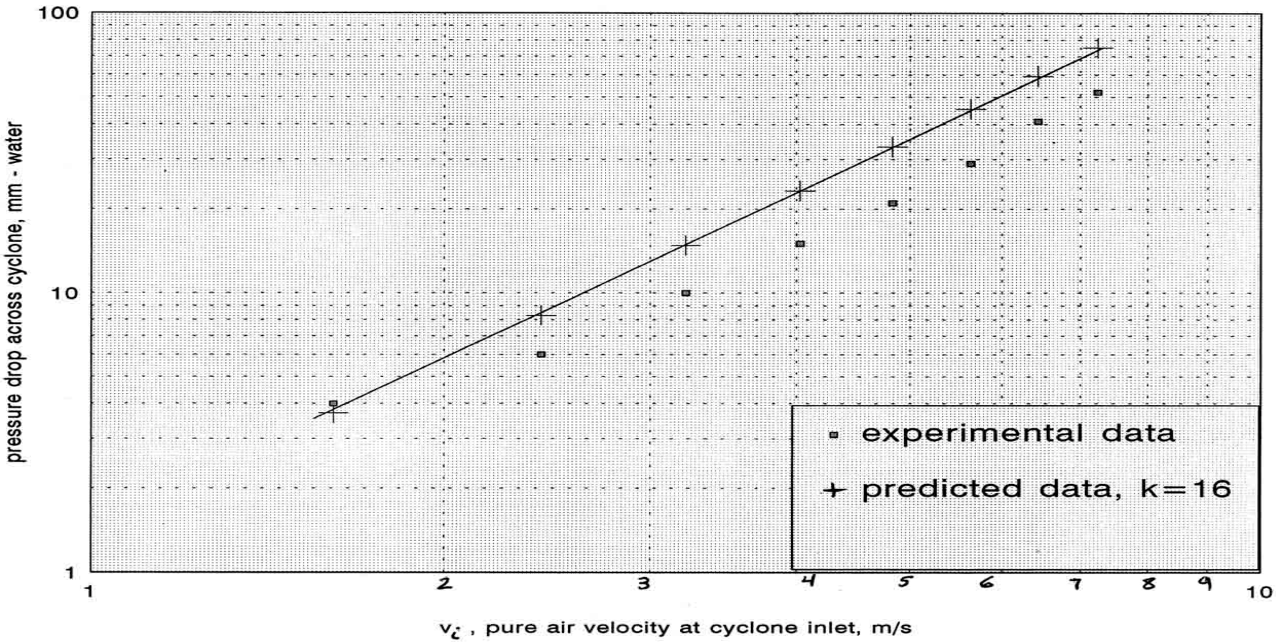

Figure 4. Pure air pressure drop in tangential cyclone comparison of experimental data with those predicted from Lapple and Shepherd's formula.

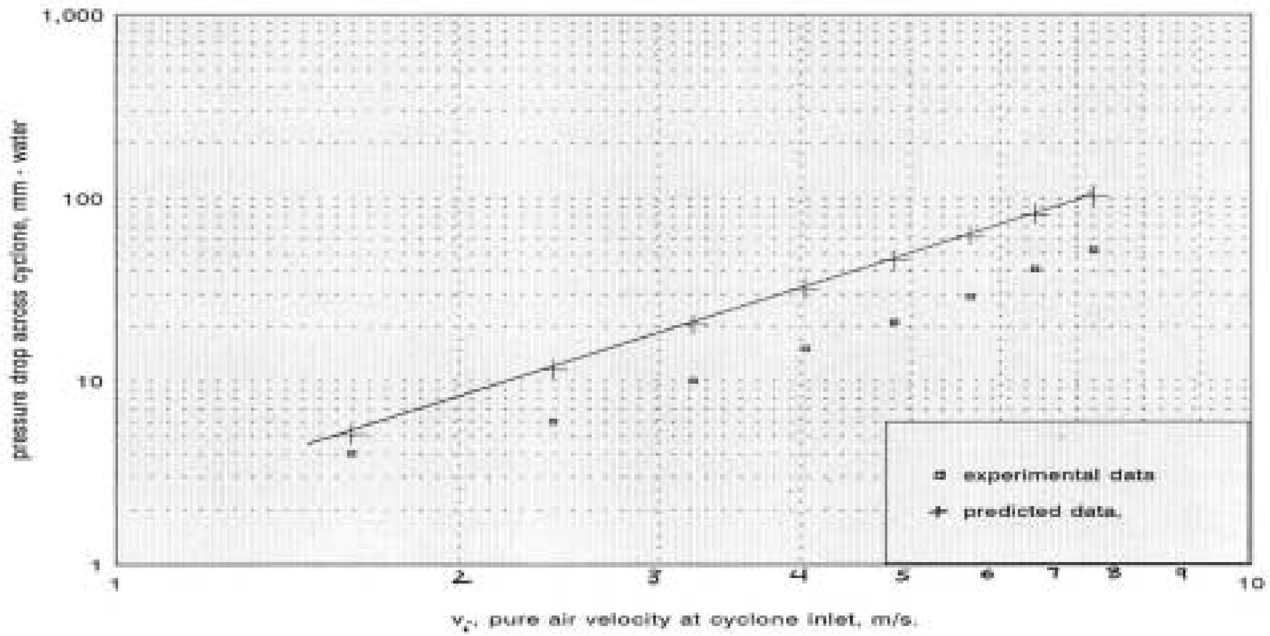

Figure 5. Pure air pressure drop in tangential cyclone comparison of experimental data with those predicted from First's formula.

D. Effect of the Cyclone Dimensions on Pressure Drop Detailed analysis of Equation 22 shows that:

1. Pressure drop in a tangential cyclone increases with increasing of the length of cylindrical and conical sections of the cyclone, while the other

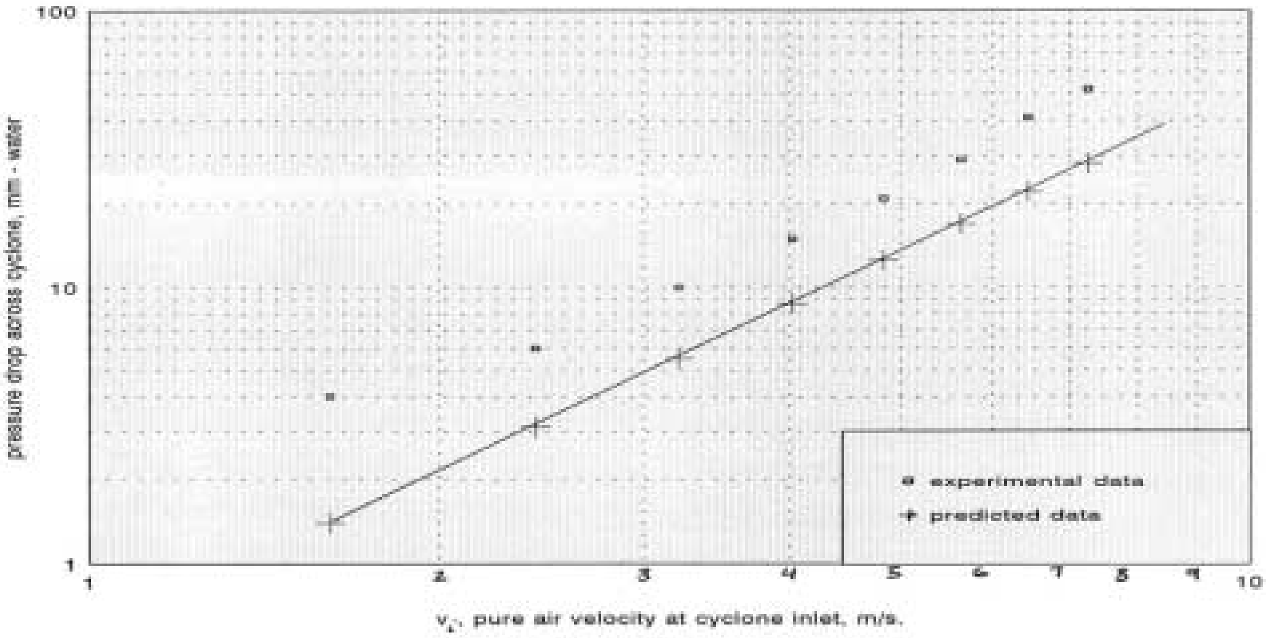

Figure 6. Pure air pressure drop in tangential cyclone comparison of experimental data with those predicted from Stairmand's formula.

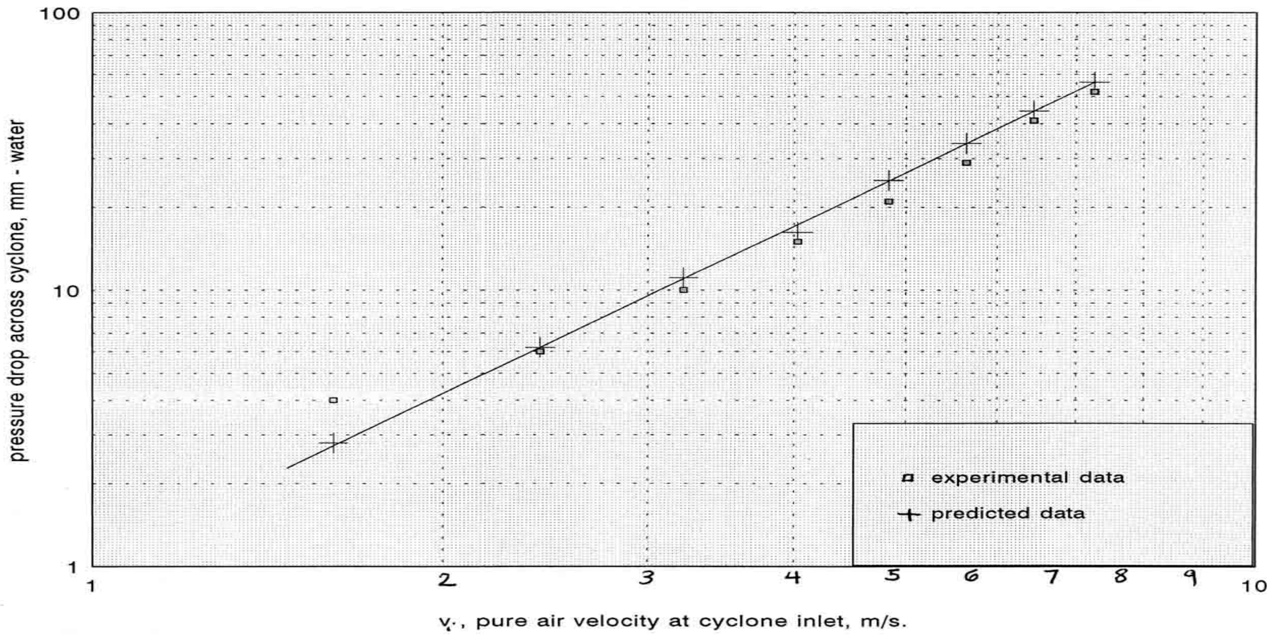

Figure 7. Pure air pressure drop in tangential cyclone comparison of experimental data with those predicted from Alexander's formula.

dimensions are retained unchanged.

2. Pressure drop increases with decreasing of the clean gas exit pipe diameter.
3. Pressure drop decreases as β, which is the angle of the inclination of the conical section of cyclone with respect to horizon, is decreased.

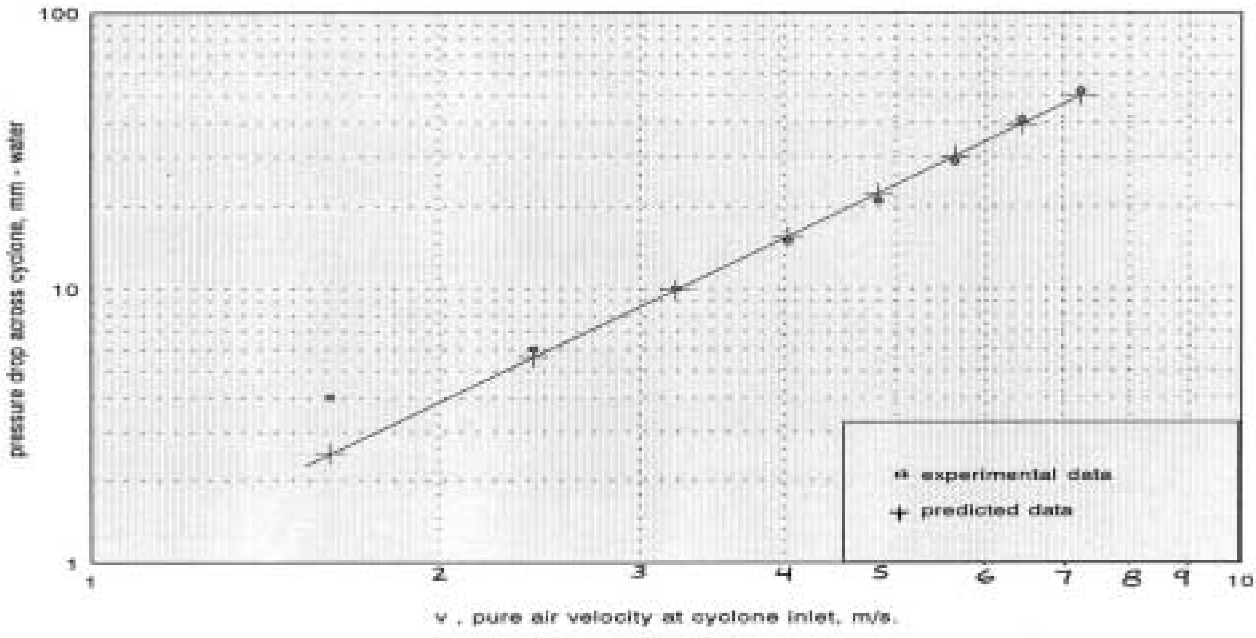

Figure 8. Pure air pressure drop in tangential cyclone comparison of experimental data with those predicted from our purposed formula.

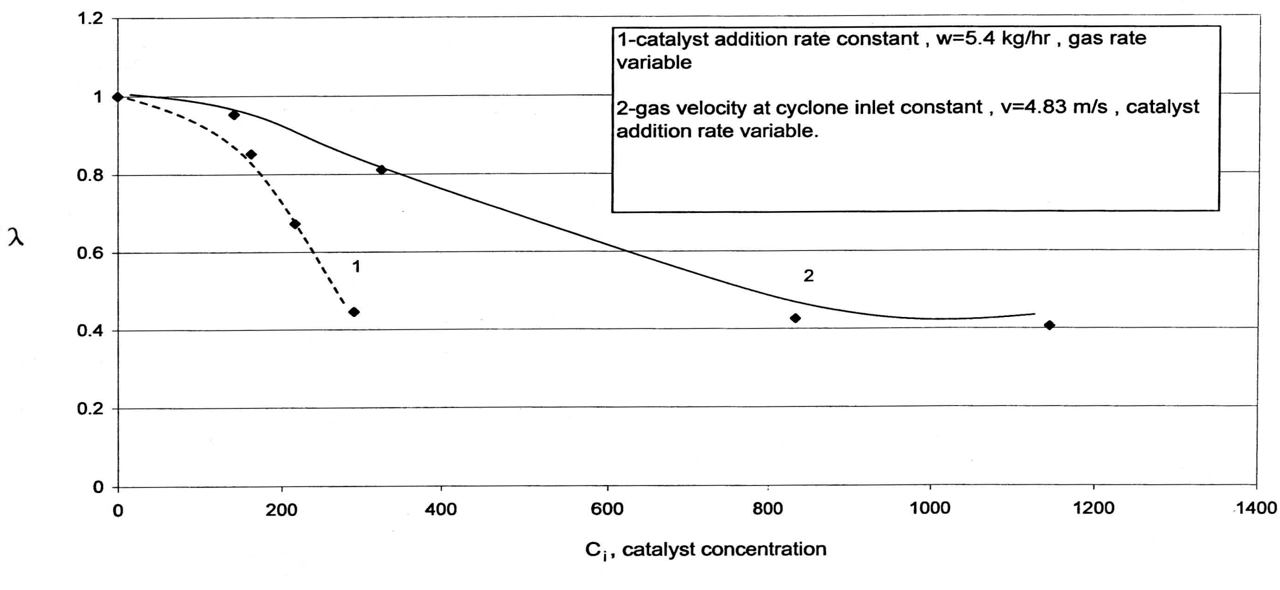

Figure 9. Variation of λ with catalyst concentration.

4. Pressure drop increases as the cross sectional area of the inlet pipe A_i, is decreased.

In summary, any change in a dimension of the cyclone that would results in an increase in ΔH, would cause the pressure drop within the cyclone to be increased.

E. Particles Separation Efficiency Free flowing zeolite catalyst with the characteristics shown in Table 6, was chosen as the solid part of the gas-solid feed to the cyclone in all the experiments. In Experiments 14 to 17, catalyst addition rate to the system was retained constant and catalyst to air ratio was varied by altering airflow rates. In Experiments 17 to 20, air flow

TABLE 4. Experimental Results of Determination of λ.

Experiment No.	N_{dusty} ---------	λ -------	V_i (m/s)	C_i (gr/m^3)
14	2.2	0.446	2.42	289.3
15	3.3	0.673	3..22	216.1
16	4.2	0.852	4.03	162.2
17	4.7	0.953	4.83	140..9
18	4.0	0.811	4.83	323.7
19	2.1	0.426	4.83	833.7
20	2.0	0.406	4.83	1145.2

Note: N_{clean} for the cyclone employed in the above experiments, was found to be 4.93.

TABLE 5. Experimental Results of Gas/Solid Mixture Pressure Drop in the Tangential Cyclone and Comparison of the Results with Predictions from Brigg's and our Proposed Equations.

Exp. No.	Air Flow Rate (m^3/hr)	Catalyst Flow Rate (Kg/hr)	C_i (gr/m^3)	V_i (m/s)	Experimental Pressure Drop (mm-H_2O)		Predicted Pressure Drop from our Formula (mm-H_2O)		Predicted Pressure Drop from Brigg's Eq. (mm-H_2O) Dusty
					Clean	Dusty	Clean	Dusty	
14	18.78	5.43	289.3	2.42	6	5	5.8	5.1	5.2
15	25.04	5.41	216.1	3.22	10	8.5	9.7	8.4	8.9
16	31.30	5.08	162.2	4.03	15	13.0	15.0	13.3	13.5
17	37.56	5.29	140.9	4.83	21	20.0	21.7	21.1	19.1
18	37.56	12.16	323.7	4.83	21	19.0	21.7	19.7	18.2

TABLE 6. Physical Properties and Size Analysis of the Solid Particles that were Used in Gas/Solid Separation Experiments.

TESTS	**RESULTS**
Particle density, ρ_p , Kg/m^3	1600
Pore volume, cc/gr	0.36
Size Distributions:	
0 - 20 micron	Nil
20 - 40 micron	0.9 wt%
40 - 80 micron	43.1 wt%
80^+ micron	56.0 wt%
Average Particle Size (A.P.S), micron	83.0

TABLE 7. Comparison of Experimental Overall Separation Efficiencies (I) with Those Predicted from Leith and Licht Original Formula (II) and Those from Our Modified and Proposed Formula (III).

Exp. No.	Air FlowRate, m^3/hr	V_i (m/s)	Catalyst Rate, Kg/hr	C_i ($gr//m^3$)	l	ς (I)	ς (II)	ς (III)
14	18.78	2.42	4.96	289.3	0.446	0.9915	0.9972	0.9823
15	20.04	3.22	5.41	216.1	0.673	0.9922	0.9983	0.9938
16	31.30	4.03	5.06	162.2	0.852	0.9930	0..9989	0.9975
17	37.56	4.83	5.45	140.9	0.953	0.9944	0.9992	0.9986
18	37.56	4.83	12.16	323.7	0.811	0.9940	0.9992	0.9981
19	37.56	4.83	31.31	833.7	0.426	0.9920	0.9992	0.9933
20	37.56	4.83	43.02	1145.2	0.406	0.9910	0.9992	0..9928

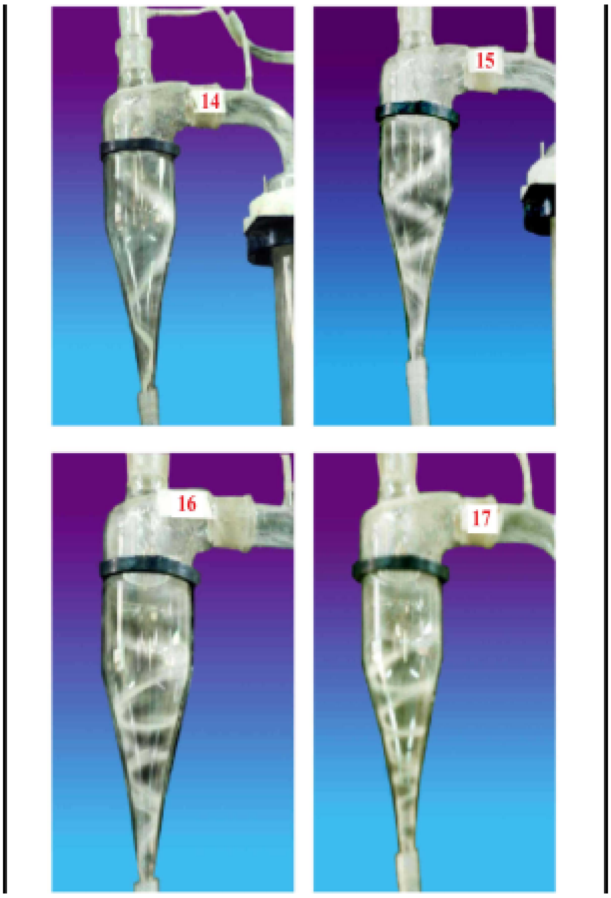

Figure 10. Number of turns of solids on the t/g cyclone wall changes with solid concentrations (Experiment 14 to 17).

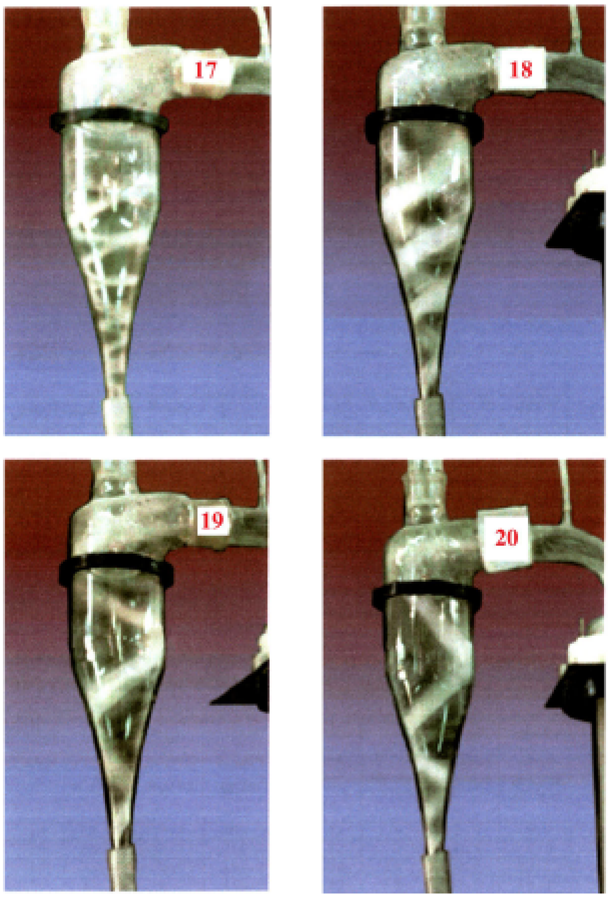

Figure 11. Spiraling path of solids in a t/g cyclone (Experiment 17 to 20).

rates were constant and catalyst to air ratio was altered by changing of catalyst rates. In all the experiments, overall separation efficiency of particles was measured and the results were tabulated in Table 7.

To check the experimental results with the theoretical predictions, theoretical calculations were carried out too. Table 7 compares the experimental results with the theoretical predictions. As is seen in the table, the proposed modifications improve the results of the Lieth and Licht equation.

10. CONCLUSIONS

This study led to the following conclusions:

1. Development of an equation to determine the number of revolutions of clean gas and lean gas/solid mixtures in a tangential cyclone.
2. Defining clearly the λ parameter and the reasons why it is not theoretically measurable.
3. Development of a new formula for prediction of pressure drops in tangential cyclones, which is able to predict the effect of variation of the cyclone's dimensions on its pressure drop.
4. Correction of the Lieth and Licht formula for prediction of the particles fractional separation efficiencies and proposing a relation, which tries to connect the cyclones' pressure, drops to their fractional separation efficiencies.

11. AKNOLEDGEMENTS

The author wishes to tank the ministry of the petroleum of the Islamic Republic of Iran for the financial supports of this project.

12. NOTATIONS

A = Cyclone's inlet port cross sectional area [m^2]
a = Cyclone's inlet port's height [m]
b = Cyclone's inlet port's width [m]
C = Cyclone's geometrical constant
D = Diameter [m]
$\bar{D}$ = Equivalent diameter as defined by Equation 7 [m]
f = Fanning friction factor
G = Parameter as defined in Table 1
ΔH = Number of gas velocity head
K = Correction factor
L_1 = Cyclone's cylindrical section's length [m]
L_2 = Cyclone's conical section's height [m]
l = Parameter as defined by Equation II in Appendix I [m]
n = Vortex exponent as defined by Equation 24
N = Number of turns of spiraling flow in the cyclone
R = Radius [m]
$\bar{R}$ = Parameter as defined by Equation 16 [m]
S = One of the cyclone dimensions as shown in Figure 2 [m]
T = Absolute temperature [ºK]
t = Solids' average residence time [s]
V = velocity [m/s]

13. GREEK LETTERS

α = Angle of spiraling path of down going particles on the cylindrical Walls of the cyclone with respect to horizon. [ºR]
α' = Angle of spiraling path of descending particles on the conical walls of the cyclone with respect to horizon. [ºR]
α'' = Angle of spiraling path of ascending flow in the central core o the cyclone with respect to horizon. [°R]
β = Angle of inclination of the conical part of the cyclone with respect to horizon. [°R]
φ = The parameter as defined in Table 1
η = Particles' fractional efficiency
λ = Parameter as defined by Equation 9
μ = Gas viscosity [Kg/m/s]
ρ = Gas density [Kg/m^3]
ρ_p = Particles density [Kg/m^3]
ψ = The modified inertia parameter as defined by Equation 25

14. INDICES

C= Cyclone
e = Exit
i = Inlet
pc = Particule 's critical

clean = Clean gas
dusty = dusty gas

After applying the above sizes in Equations I, II and III, C was found to be 25.335.

15. APPENDIX I

The geometry coefficient C, is calculated from:

$$c=\frac{\pi D_c^2}{ab}\left\{2\left[1-(\frac{D_e^2}{D_C^2})\right](\frac{S}{D_C}-\frac{a}{2D_C})+(\frac{S+l-L_1}{D_C})(1+\frac{d_c}{D_C}+\frac{d_c^2}{D_C^2})+\frac{L_1}{D_C}-(\frac{D_e}{D_C})^2(\frac{l}{D_C})-\frac{S}{D_C}\right\} \quad \text{(I)}$$

$$l=2.3D_e\left[\frac{D_C^2}{ab}\right]^{\frac{1}{3}} \quad \text{(II)}$$

$$d_c=D_C-\frac{(D_C-B)(S+l-L_1)}{L_2} \quad \text{(III)}$$

If $l \succ (L_1+L_2-S)$, then set $l=L_1+L_2-S$ in both Equations (I) and (III).

In our experiment the above dimensions were:

$D_C=0.093\text{m}$	$S=0.068\text{m}$
$a=0.048\text{m}$	$B=0.020\text{m}$
$b=0.045\text{m}$	$L_1=0.155\text{m}$
$D_e=0.040\text{m}$	$L_2=0.165\text{m}$

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