A New Correlation for Holdup in Gas-Solids Cyclone

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Abstract: - The performance of cyclone as gas to solids heat exchanger depends on the surface area of holdup of the solid particles inside the cyclone. Unlike the conventional heat exchangers where heat transfer area is fixed for a particular heat exchanger, heat transfer area in the cyclone pre heater varies with operating parameters. Therefore, present investigation is aimed to study the effect of solid feed rate (0.5–7.5 g/s), cyclone inlet air velocity (9–22 m/s), and particle sizes (163–460 mm) on the holdup in a given cyclone. The existing correlations for prediction of holdup are reviewed. A new correlation is also proposed using step wise regression based on Marquardt-Levenberg algorithm. The new correlation is found to be better than the existing correlations.

Key-Words: - Cyclone, Holdup, Correlation, Regression, Marquardt-Levenberg algorithm

1 Introduction

Traditionally, cyclones are used in pollution control and fine products recovery in the industries due to their inherent ability to separate solid particles from gases. In recent years, the use of cyclone as a gas to solids heat exchanger is also gaining popularity. The cyclone heat exchangers have large potential of being used as heat recovery equipment where hot processing of solid particles may be allowed in direct contact with hot gases like in fertiliser, polymer powder, pharmaceutical and food-processing industries. Cyclone as heat transfer equipment may also be used for solidification, drying, water removal, solvent recovery, sublimation, chemical reaction, and oxidation. In all such cases, performance of cyclone depends on the surface area of holdup of the solid particles inside the cyclone. Since the holdup varies with the variation in operating parameters, heat transfer area also varies with the variation in these parameters. This is unlike the conventional indirect contact heat exchangers where heat transfer area is fixed for a particular heat exchanger irrespective of operating conditions [1]. The holdup mass of the solids, therefore, plays an important role in heat transfer in a cyclone. The above fact adds to the complexity in the design of cyclone heat exchanger and calls for the measurement and prediction of holdup, precisely.

A review of the literature reveals that limited information is available about holdup in cyclone. Szekely and Carr [2], Raju [3], Yen et al. [4] and Raju et al. [5], Jain [6] carried out experimental studies to measure holdup. The details of the cyclone and the gas and the solid phases used in respective studies are compiled in Table 1. All the researchers considered plug flow in the cyclone, i.e., first particle in-first particle out flow pattern. Yen et al. [4] confirmed it experimentally. Yen et al. [4] observed the flow patterns in a transparent cyclone and measured the particles residence time distribution in cyclone. The responses indicate that the flow pattern of the solid particles in the cyclone is a plug flow if the gas velocity is high and the solids flow rate is large enough. Szekely and Carr [2] also carried out a series of runs with bronze particles along with plug of iron particles. The solid particles at the outlet were ducted into a glass tube, diameter 0.5” (12.7 mm). It was noted that, in all cases, the plug of iron particles had maintained its identity with clearly defined boundaries at each end. This confirms the existence of plug flow pattern.

Szekely and Carr [2] obtained the numerical values of average particles residence time computed on the basis of plug flow in the range from 0.86 to 1.05 s. Considering plug flow of solid particles, Yen et al. [4] computed the mean residence time of solid particles in cyclone as holdup weight of the solid particles divided
by the solids feed rate. Following correlation for the mean residence time of particles was proposed by Yen et al. [4]

\[
\frac{t_p}{D_C} = \left( \frac{d_p}{1.27 \times 10^{-3}} \right)^{-0.125} \left( \frac{m_s}{m_g} \right)^{0.7} \left( \frac{v_{Ci}^2}{D_C g} \right)^{0.5}
\]

(1)

where \( t_p \) is particle residence time, \( v_{Ci} \) is velocity of air at cyclone inlet, \( D_C \) is Diameter of cyclone, \( d_p \) is diameter of particles, \( m_s \) is solids feed rate, \( m_g \) is mass flow rate of air, \( g \) is acceleration due to gravity.

### Table 1 Details of studies on gas-solids cyclone

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><strong>Cyclone</strong></td>
<td>Reverse flow</td>
<td>Reverse flow</td>
<td>Reverse flow</td>
</tr>
<tr>
<td></td>
<td><strong>Entry</strong></td>
<td>Tangential</td>
<td>Tangential</td>
<td>Tangential</td>
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<tr>
<td></td>
<td><strong>Position</strong></td>
<td>Vertical</td>
<td>Vertical</td>
<td>Vertical</td>
</tr>
<tr>
<td></td>
<td><strong>Dimensions of cyclone (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diameter of cylindrical part, ( D_C )</td>
<td>120</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Height of cylindrical part, ( h )</td>
<td>170</td>
<td>125</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Total height of cyclone, ( H )</td>
<td>480</td>
<td>388</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Depth of cyclone inlet, ( a )</td>
<td>60</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Width of cyclone inlet, ( b )</td>
<td>25</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Diameter of air exit, ( D_e )</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2.</td>
<td><strong>Gas</strong></td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td></td>
<td><strong>Solid particles</strong></td>
<td>Cement raw meal, sand</td>
<td>Sand</td>
<td>Sand</td>
</tr>
<tr>
<td></td>
<td><strong>Density (kg m(^{-3}))</strong></td>
<td>2823, 3280</td>
<td>2643</td>
<td>3000</td>
</tr>
<tr>
<td>3.</td>
<td><strong>Operating parameter range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solids feed rate (g s(^{-1}))</td>
<td>2-10</td>
<td>1-9</td>
<td>0.5-7.5</td>
</tr>
<tr>
<td></td>
<td>Cyclone inlet gas velocity (m s(^{-1}))</td>
<td>8-16</td>
<td>6-16</td>
<td>9-22</td>
</tr>
<tr>
<td></td>
<td>Particles size (( \mu m ))</td>
<td>77, 170</td>
<td>294-595</td>
<td>163-460</td>
</tr>
</tbody>
</table>

Considering plug flow, the holdup \( (M_h) \) may be computed from average particles residence time as:

\[
M_h = m_s \frac{t_p}{D_C}
\]

(2)

Thus, determination of holdup shows that holdup increases with increasing solids feed rate \( (M_h \propto m_s^{0.3}) \), increasing inlet gas velocity \( (M_h \propto v_{Ci}^{0.7}) \) and decreasing particles size \( (M_h \propto d_p^{-0.125}) \). The effect of particles size on holdup is insignificant in comparison to other to parameters, namely, solids feed rate and inlet air velocity.

A correlation for the prediction of volume fraction of solid particles \( (\epsilon) \) in cyclone, i.e., ratio of volume of holdup of solid particles to volume of cyclone \( (V_C) \) is obtained by Raju et al. [5] as given in equation, Eq. 3

\[
\epsilon = 0.0027 F_m
\]

(3)

Eq. 3 given by Raju et al. [5] shows that volume fraction in cyclone depends upon solids to gas loading ratio \( (F_m) \) only. Holdup may be computed from Eq. 4 using the estimated volume fraction from Eq. 3

\[
M_h = \epsilon \rho_s V_C
\]

(4)

Estimation of holdup indicates that holdup increases with increasing solids feed rate \( (M_h \propto m_s) \) and decreasing inlet gas velocity \( (M_h \propto v_{Ci}^{-1.0}) \).

Both the investigators have shown that holdup increases with increasing solids feed rate however at different rates. Where Yen et al. [4] observed increase in holdup with increasing inlet air velocity Raju et al. [5] obtained increase in holdup with decreasing solids feed rate. Therefore, more experimental data are required to check these trends. Moreover, holdup computed from these correlations for the same condition differs from each other. Reason for this discrepancy may be attributed to the cyclones of different dimensions used in these investigations. These correlations do not appear to represent proper cyclone dimension on which holdup is based. This calls for further investigation on holdup and development of a better correlation.
2 Experimental set-up and procedure

An experimental setup is developed to collect data to study the effect of variation of air velocity, solids feed rate and particles size on holdup. The schematic of experimental set-up is shown in Fig. 1. It basically consists of four segments, namely, a tangential entry reverse flow cyclone with solids receiver bin (main test section), an air flow and heating system, a solids handling & feeding system and necessary instrumentation for measurement and control.

Sand particles collected between two screens of standard series are considered to represent particles of size equal to arithmetic average of the openings of screens. Based on the above assumption, sand of four different particle sizes (163, 274, 359, 460 \( \mu m \)) were segregated and used in the present study. A typical experimental procedure consists of adjusting airflow rate using the bypass valves (V1 and V2) to achieve the desired inlet velocity. The inlet air velocity was measured with orifice meter (10). The particles of a particular average size, stored in the hopper (1), were fed into the air stream through conical funnel (3) and venturi ejector (5) with the help of an electromagnetic arm imparting vibrations to channel feeder (2). A steady solid feed rate was achieved for a particular combination of particle size, gas velocity, and the funnel opening. All the instruments used for measurement in the present study were suitably calibrated. The details of experimental setup and procedure is outlined in Jain[6], Jain et. al [1].

Using the procedure as used by Szekely and Carr [2], Raju [3] and Yen et al. [4], the holdup in the present investigation was obtained by collecting the solids in a cup provided inside the solids receiver bin, when the solids flow and air flow were simultaneously switched off. The collected holdup was measured on self calibrating digital weighing balance having least count 0.0001 g. In all 100 runs are made for 5 air velocities between 9 to 22 m s\(^{-1}\) \( \times 5 \) solid flow rates between 0.5 to 7.5 g s\(^{-1}\) \( \times 4 \) particle sizes (163, 274, 359, 460 \( \mu m \)). In order to reduce the uncertainty, 5 samples of holdup are collected for each run and their average is used.

![Fig.1 Sectional view of the experimental setup](image)


3 Comparison between Experimental Holdup and those Predicted from the Existing Correlations

As described in Section 1, the correlation for average particles residence time given by Yen et al. [4] and
the correlation for volume fraction of the holdup given by Raju et al. [5] may be used to compute the holdup in a cyclone for the purpose of comparison with present experimental data.

3.1 Comparison between experimental holdup and those predicted from correlation proposed by Yen et al. [4]
The experimentally determined holdup is compared with the holdup computed from Eq. (1) in conjunction with Eq. 2, in Fig. 2.

![Graph showing experimental verses predicted holdup from the correlation of Yen et al. [4], Eq. 1.](image)

**Fig. 2** Experimental verses predicted holdup from the correlation of Yen et al. [4], Eq. 1

The above correlation predicts the present data within an error of + 200 % to - 50 %. Moreover, points are not evenly distributed around the 45° line. At lower values of the holdup, the correlation over predicts while at higher values of the holdup, the correlation under predicts. This skewness in the data reveals that the trends of predicted holdup do not match satisfactorily with the present experimental data. The reason for this discrepancy may be attributed to the fact that the size of the cyclone used in the present investigation is different from the cyclone for which the correlation was developed. In fact, size of cyclone is one of the important parameters for the computation of the holdup. It appears that the correlation, Eq. 1, proposed by Yen et al. [4] is specific to their experimental work and geometrical dimensions of their cyclone. Further, this correlation does not appear to include all the pertinent cyclone dimensions to make it more general.

3.2 Comparison between experimental holdup and those predicted from correlation proposed by Raju et al. [5]
Using Eq. 3 along with Eq. 4, the holdup is computed for the parameters of the present investigation and compared with corresponding experimental values in Fig. 3.
Figure 3 shows that the correlation given by Raju et al. [5] predicts the present experimental data within an error band of +75 to -40 %, which seems to be better than correlation given by Yen et al. [4]. Further, it may also be seen that scatter of points around the 45° line is comparatively even.

The deviation in the values of the holdup predicted by correlation, Eq. (3), of Raju et al. (1994) from the present data may again be attributed to the difference in size of cyclone used in present investigation from that used by Raju et al. [5]. It may be noted that, though the correlation given by Raju et al. [5] is simpler than one given by Yen et al. [4], the later predicts the holdup more accurately. It appears that the improvement in the prediction of the holdup by Raju et al. [5] model over Yen et al. [4] model is primarily due to the inclusion of volume of cyclone for the computation of the holdup.

It is evident from the above discussion that the existing correlations do not predict the holdup satisfactorily for the cyclone of the sizes other than those used by these investigators. This calls for the need of a more general correlation for the computation of the holdup.

4 Development of a New Correlation for Holdup

Based on the data gathered in the present study a correlation for the holdup is developed. For this purpose, important dimensionless groups are determined by dimension analysis which addresses to all pertinent parameters and then a correlation is developed using stepwise regression analysis which is derived from Brandon’s method given by Kafarov [7]. The regression uses the Marquardt-Levenberg algorithm [8] to find the coefficients of the independent variables that give the best fit between the equation and the data. This algorithm seeks the values of the coefficient and exponents that minimise the sum of the squared differences between the values of the observed and predicted values of the dependent variable in the correlation model.

4.1 Identification of pertinent parameters affecting holdup

As discussed earlier, in addition to three basic operating parameters, namely, solids feed rate, inlet air velocity and particles size, relevant cyclone dimensions should be included in the correlation to broaden the scope of its applicability. A further analysis of movement of solid particles under the influence of various forces inside the cyclone reveals the important geometrical parameters of the cyclone, which influence the holdup.
It should be noted that particles inside a cyclone move under the influence of centrifugal force, air drag, gravity force, buoyancy force and frictional force, all acting simultaneously. The solids holdup is directly proportional to the axial drag force experienced by the particles as it influences the axial motion of the particles from top inlet to the bottom exit of the cyclone. An analysis of axial drag force shows that it depends upon relative axial air velocity with respect to solid particles, drag coefficient and particles size. The average axial air velocity depends upon annulus area of the cyclone. Therefore, annulus area is a significant cyclone dimension, which governs the holdup. Since the annulus area varies in the conical section of the cyclone, an average cyclone annulus area is considered and is defined as annulus volume divided by the height of cyclone. Thus, average annulus area of cyclone ($A_{CA}$) is included as a parameter representing critical cyclone dimension in the correlation for the estimation of holdup.

Based on above discussion, holdup is considered as a function of solids feed rate, air velocity, particles size and average annulus area of cyclone. Mathematically, it may be represented as:

$$M_h = f(m_s, v_{Ci}, d_p, A_{CA})$$

(5)

The above-identified parameters are converted into dimensionless groups for the development of the empirical correlation, as follows

4.2 Dimensional analysis

In order to convert the identified parameters into non-dimensional forms, diameter of cyclone is chosen as independent parameter. Dimensional analysis provides following four dimensionless numbers. These are solids to air loading ratio ($F_m = m_s / m_a$), ratio of particles diameter to cyclone diameter ($d_p / D_c$), cyclone Froude number ($F_{rC} = v_{Ci}^2 / g D_c$) and a dimensionless number ($M_h / A_{CA} D_c \rho_s$).

Solids to air loading ratio is used by both Yen et al. [4] and Raju et al. [5]. Ratio of particles diameter to cyclone diameter, and cyclone Froude number are used by Yen et al. [4]. Froude number represents the ratio of inertial force to gravity force. As clear from the earlier discussion, the holdup is expected to be proportional to annulus area. Therefore, it is grouped with the holdup giving the fourth dimensionless group as $(M_h / A_{CA} D_c \rho_s)$, which may be termed as ‘dimensionless holdup’. These groups, in general, are related as follows

$$\left( \frac{M_h}{A_{CA} D_c \rho_s} \right) = a_1 \left( \frac{m_s}{m_a} \right)^{a_2} \left( \frac{v_{Ci}^2}{g D_c} \right)^{a_3} \left( \frac{d_p}{D_c} \right)^{a_4}$$

(6)

4.3 Regression analysis

The values of coefficient and exponents in the correlation for holdup, Eq. 6, are obtained following the stepwise regression analysis as detailed below.

In first step, regression analysis is carried out taking one dimensionless group at a time. In this step, a single dimensionless number is identified which on regression provides the least sum of square of error (SSE). The results of first step regression analysis are presented in Table 2.
Table 2 Results of first step regression for developing correlation for the holdup

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Correlation</th>
<th>SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \frac{M_h}{A_{CA} D_c \rho_i} = 0.0129 \left( \frac{m_s}{m_a} \right)^{0.70} )</td>
<td>0.003105</td>
</tr>
<tr>
<td>2.</td>
<td>( \frac{M_h}{A_{CA} D_c \rho_i} = 0.0014 \left( \frac{v_{Ci}}{g D_c} \right)^{0.24} )</td>
<td>0.0011567</td>
</tr>
<tr>
<td>3.</td>
<td>( \frac{M_h}{A_{CA} D_c \rho_i} = 0.04 \left( \frac{d_p}{D_c} \right)^{-0.36} )</td>
<td>0.0009327</td>
</tr>
</tbody>
</table>

The value of sum of square of errors for solids loading ratio is significantly less than that for other two groups. This shows that \( \left( \frac{m_s}{m_a} \right) \) is the most essential group to be incorporated in the correlation. This is in line with the earlier discussion. The holdup as predicted by this correlation is compared with the experimental holdup in Fig. 4. The figure shows that this correlation predicts the holdup within an error range of +50% to -40%. The high value of error band suggests that more than one dimensionless group is required for the correlation to bring down the error band to an acceptable limit.

The second important dimensionless group is identified by studying the interaction of \( \left( \frac{m_s}{m_a} \right) \) with the remaining two dimensionless numbers one by one in the second step of regression. The results of second step of regression analysis are presented in Table 3.

Table 3 Results of second step regression for developing correlation for the holdup

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Correlation</th>
<th>SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \frac{M_h}{A_{CA} D_c \rho_i} = 0.00096 \left( \frac{m_s}{m_a} \right)^{1.00} \left( \frac{v_{Ci}}{g D_c} \right)^{0.54} )</td>
<td>0.00001030</td>
</tr>
<tr>
<td>2.</td>
<td>( \frac{M_h}{A_{CA} D_c \rho_i} = 0.013 \left( \frac{m_s}{m_a} \right)^{0.70} \left( \frac{d_p}{D_c} \right)^{0.04} )</td>
<td>0.00031046</td>
</tr>
</tbody>
</table>
The results show that first correlation in Table 3 gives least sum of square of error. It is significantly less than the least SSE obtained in first step. Hence, \( \left( \frac{m_c}{m_a} \right) \) when taken together with \( \left( \frac{v_c^2}{g \ D_c} \right)^{0.54} \) forms most important pair for the correlation. The result of this correlation as shown in Fig. 5 suggests that this is a reasonable fit within an error of +15% to –10%.

However, third step regression is also carried. When all the three dimensionless groups are taken together, the sum of square of errors comes out to be 0.00000892 and the correlation is obtained as given below.

\[
\frac{M_k}{A_{CA} \ D_c \ \rho_s} = 0.00069 \left( \frac{m_c}{m_a} \right)^{1.02} \left( \frac{v_c^2}{g \ D_c} \right)^{0.54} \left( \frac{d_p}{D_c} \right)^{-0.055} \tag{7}
\]

SSE does not show any appreciable improvement. Moreover, exponent of \( \left( \frac{d_p}{D_c} \right) \) being small shows that holdup is not a strong function of particle size as already identified by the others also. Therefore, correlation at serial number 1 of Table 3 is finally selected. The correlation is obtained for solids loading ratio range from 0.05 to 0.87 and Froude number range from 82 to 552.

### 5 Statistical Analysis of Correlation for Holdup

Further a statistical analysis of the proposed correlation for holdup is carried out to ascertain the accuracy of fit. The standard error and coefficients of variation in the coefficients and exponents are used as yard sticks to figure out accuracy of the fitted curve. Therefore, standard error and coefficient of variation in each parameter obtained by regression are displayed in Table 4.

#### Table 4 Statistics of the parameters of the proposed correlation for the holdup

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters in Eq. 5</th>
<th>Value of the parameter</th>
<th>Standard error of the parameter</th>
<th>Coefficient of variation of the parameter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( a_1 )</td>
<td>9.5739E-4</td>
<td>0.5185E-4</td>
<td>5.416</td>
</tr>
<tr>
<td>2.</td>
<td>( a_2 )</td>
<td>1.0046</td>
<td>0.0142</td>
<td>1.412</td>
</tr>
<tr>
<td>3.</td>
<td>( a_3 )</td>
<td>0.5365</td>
<td>0.0105</td>
<td>1.958</td>
</tr>
</tbody>
</table>

The low values of coefficients of variation and standard errors show good accuracy of the fitted curve.

Further, predicted holdup from the proposed correlation are statistically analysed and compared with the present experimental holdup values. The analysis of variance (ANOVA) provides \( R^2 \) value (sum of square of residue) equal to 0.9867. The value of \( R^2 \) is close to 1 which signifies the strong relationship amongst the variables. To reinforce this finding further, \( F \)-characteristic test is also carried out which gives \( F \) value as 3604 with regression degree of freedom 2 and error degree of freedom 97. \( F \) value determines whether experimental holdup and predicted holdup have different variance. \( F \) probability that we are incorrect in stating that the two variances are different for 99 degree of freedom with 95% confidence level is close to zero (1 \( \times 10^{-91} \) as obtained from Microsoft Excel 97). The statistical results signify a good fit having almost same value of variance in experimental and predicted values of the holdup from the proposed correlation.

### 6 Validation of Proposed Correlation for Holdup

As shown in Fig. 6, the correlation predicts the present experimental holdup within an error band of +15 to –10%. The results signify strong relationship among the variables.
To validate further, the proposed correlation, is used to predict the experimental values of the holdup obtained by other investigators (Yen et al. [4], and Raju et al., [5]), the comparison is also shown in Fig. 6. The correlation predicts the data of these investigators within +15 to -25%. This shows significant improvement over the correlations of Yen et al. [4] and Raju et al. [5] which predict the present data of the holdup within an error band of +200 to –50 % and +75 to –40%, respectively.

7 Conclusion
In this paper, the existing correlations [4, 5] for prediction of holdup are reviewed. The outcomes are summarized below.

- At lower values of the holdup, the correlation as given by Yen et al. [4] over predicts while at higher values of the holdup, the correlation under predicts. This skewness is attributed to the fact that the size of the cyclone used in the present investigation is different from the cyclone for which the correlation was developed. But the equation (Eq. 1) developed by Yen et al. [4] does not contain the geometrical parameters of the cyclone.

- In case of the correlation (Eq. 3) proposed by Raju et al. [5], it also does not predict the holdup values correctly. It may be noted that, though the correlation given by Raju et al. [5] is simpler than one given by Yen et al. [4], the later predicts the holdup more accurately. It appears that the improvement in the prediction of the holdup by Raju et al. [5] model over Yen et al. [4] model is primarily due to the inclusion of volume of cyclone for the computation of the holdup.

To eradicate the problem, a new correlation is proposed here using step wise regression based on Marquardt-Levenberg algorithm [8]. A correlation is also proposed (Eq. 7) for the holdup in the cyclone, considering all the parameters affecting the holdup of cyclone. As shown in Fig. 6, the new correlation predicts the present experimental holdup within an error band of +15% to –10 %. Error analysis was also carried out, which signifies strong relationship among the variables, and is found to be better than the existing correlations.
References: