SLAG REJECTION IN CYCLONE COMBUSTOR

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1.0 INTRODUCTION

In the combustion of pulverized coal for applications such as MHD power generation or the retrofit of steam boilers designed for oil or gas burners, the rejection of major portions of the coal ash in the combustor is important. In the MHD case, current generator designs\(^1\) require a thin slag layer to protect the electrodes. However, this requirement can be met by the carry-over of < 20 percent of the slag from the burner. The carry-over of major portions of the slag would not necessarily affect the performance of the generator, per se, but it could present major problems to the downstream boilers and seed separation processes. For the application of retrofitting steam boilers designed for oil or gas firing, the tube spacing within such units is so close that it would lead to serious fouling problems if forced to operate under conditions of heavy slag carry-over from a conventional coal combustor.

The work reported in this paper relates to the analysis of a series of tests carried out in Poland as part of an information exchange program between Poland and the U.S.A. The tests were performed in a 4 MW cyclone design coal combustor at the Nuclear Research Institute in Swierk, Poland. The MHD Division of the Fossil Energy Branch of DOE was the cognizant U.S. agency. The program was designed to investigate the effects of various operating parameters on the performance of the cyclone burner. One operating parameter, coal particle size distribution, was found to have a dominant effect on one of the performance criteria, slag rejection, and it is this relationship that is addressed in this paper.

In their early experiments the Polish workers\(^2\) reported slag rejection levels of 70 to 75 percent when burning Polish coals. In subsequent tests using Illinois No. 6 coal they were only able to achieve slag rejection levels of between 25 and 40 percent\(^3\). A review of the properties of the U.S. and Polish coals\(^4\) indicated that the difference in the rejection levels was most likely due to differences in particle size distribution as the U.S. coal was found to be a finer grind.

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In considering the general effect of particle size on ash behavior it can be seen that, quantitatively, the centrifugal gas flow can force wall impact of relatively large particles. This can occur in a time scale small relative to their combustion time scale, and result in deposition of their mineral (ash) content on the wall. On the other hand, smaller coal particles generally have a low ballistic parameter and combust in the gas flow. Their mineral content vaporizes or is entrained in the gas flow. To be more explicit in accounting for the observed differences in the levels of ash rejection and to direct improvements in combustor design, it was decided to examine the effects of particle size on ash rejection in a quantitative manner. This was accomplished through the application of hydrodynamic and coal combustion models to the case of the design and operation of the Polish 4 MW combuster.

2.0 EXPERIMENTAL RESULTS

A cross-section drawing of the Polish Cyclone Combustor is shown in Figure 1. The inlet section to the cyclone is arranged as a scroll and the swirl blades are provided to distribute the air as uniformly as possible. The blades are mounted at 15° tilt. The air thus enters with both tangential and radial components. The coal injectors are arranged at 45° to the tangential direction and are mounted at about 75 percent of the combustor diameter, oriented in the plane of a radius vector. The combustor itself is inclined so that the slag tap is vertical to the floor.

The coal particles when injected into cyclone burner are imparted with rotational momentum by the rotating gas in the burner and consequently, particles travel toward the wall. At the same time, the radial velocity of the particles is decreased due to the drag force between particles and gas. Smaller particles have a smaller inertia and hence travel relatively slow towards the wall. Thus, depending upon the size, the particles may or may not reach the wall. The third important time scale, relates to particle burnout and ash vaporization rates. Figure 2 shows a schematic of the dynamic history of coal particle in the burner. The particles transported inertially to the wall complete burning and reject ash at the wall while those particles which
Figure 2. Schematic of Coal History in Cyclone Burner
remain suspended in the gas burn totally in the gas phase. Their mineral matter content is either entrained as small particles out of cyclone or it is transported to the walls by diffusion through the boundary layer, basically describable via a Reynolds analogy model.

The histograms of the particle size distribution of both coal types fed into the cyclone are shown in Figure 3 and the proximate analyses of the coals are shown in Table 1. A detailed summary of performance results is given in Table 2. (2-4)

3.0 ANALYSIS

The general flow pattern of gas in cyclone burners is generally recognized to be complex. (5) The gas velocity consists of three components, (i) tangential, (ii) axial and (iii) radial, and they are in general a function of radius and axial location in the burner. The tangential component is responsible for imparting the radial momentum to the particles which is either aided or opposed by the radial component of gas velocity depending upon the direction of radial flow of gas. Thus the time for particles to reach the wall is dependent upon the distribution of radial and tangential gas velocity components. The mean axial component determines the residence time of gas in the burner. With this fundamental description of the flow pattern within the cyclone, one can arrive at a set of equations for momentum balance of the particles, in all three directions, based upon assumptions of the flow field structure.

3.1 ASSUMPTIONS

In order to obtain controlling groups of variables which determine the particle time to reach the wall, the following assumptions are made to simplify the analysis:

(i) Gas velocity field assumed independent of particle momentum transport or momentum defect.

(ii) The coal particles when injected travel with the same local tangential velocity as the gas. No injection penetration or residual velocity is considered.
Figure 3. Size Distribution for Pulverized Coal
<table>
<thead>
<tr>
<th></th>
<th>Polish Bytom*</th>
<th>U.S. Ill. No. 6*</th>
<th>U.S. Ill. No. 6**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>1-3.5</td>
<td>7.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Vol. Matter (%)</td>
<td>30-36</td>
<td>33.7</td>
<td>36.9</td>
</tr>
<tr>
<td>Fixed C (%)</td>
<td>61-66</td>
<td>45.2</td>
<td>42.95</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>15.3-22.8</td>
<td>13.2</td>
<td>13.14</td>
</tr>
<tr>
<td>HHV (Btu/lb)</td>
<td>10,780</td>
<td>11,540</td>
<td></td>
</tr>
</tbody>
</table>

*Analysis performed in Poland.

**Analysis performed in U.S.
**TABLE 2. TEST RESULTS**

<table>
<thead>
<tr>
<th></th>
<th>Bytom</th>
<th>I11. No. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Temp. (°K)</td>
<td>2700-2900</td>
<td>2450-2720</td>
</tr>
<tr>
<td>Plasma Conductivity (Mho/m)</td>
<td>3</td>
<td>4-5</td>
</tr>
<tr>
<td>Heat Loss (%)</td>
<td>14-20</td>
<td>11-12</td>
</tr>
<tr>
<td>Seed Loss (%)</td>
<td>15-20</td>
<td>5</td>
</tr>
<tr>
<td>Slag Rejection (%)</td>
<td>71-76</td>
<td>25-41</td>
</tr>
<tr>
<td>Unburned Carbon (%)</td>
<td>&lt;1</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Pressure Fluctuation (%)</td>
<td>+1</td>
<td>+1.5</td>
</tr>
<tr>
<td>Operating Pressure (atm.)</td>
<td>2.80</td>
<td>2.85</td>
</tr>
</tbody>
</table>
(iii) The local tangential velocity ($v_t$) of gas is given by the following law:

$$v_t r^l = \text{constant} \quad (1)$$

where

- $l = 1$ for free vortex flow
- $l = -1$ for forced vortex flow
- $r$, radial position in combustion chamber

(iv) The coal particle takes a finite time to heat up but devolatilizes instantaneously. The char particles burn under diffusion control with constant density.

(v) The drag coefficient is given by the following, assuming simple spherical particles.

$$C_d/2 = A/Re^m \quad (2)$$

$C_d$, friction coefficient
$Re$, Reynolds number $|V_r - v_r| d_p/\nu$
$d_p$, particle diameter
$\nu$, kinematic viscosity
$A, m$, constants
$V_r$, radial velocity of particle
$v$, radial velocity of gas

<table>
<thead>
<tr>
<th></th>
<th>$Re &lt; 1$</th>
<th>$1 &lt; Re &lt; 1000$</th>
<th>$Re &gt; 1000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>12</td>
<td>15</td>
<td>0.22</td>
</tr>
<tr>
<td>$m$</td>
<td>1</td>
<td>0.625</td>
<td>0</td>
</tr>
</tbody>
</table>

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(vi) The radial gas velocity is assumed independent of radius and treated as a parameter in the analysis to characterize particle trajectories.

(vii) For quantitative results in studying the effects of particle size on slag rejection, it will be further assumed that the initial radial velocity of the particle is zero and the density of the particles corresponds to char density.

(viii) The residence time of a suspended particle is the same as the gas residence time.

Assumption (i) is justifiable in view of the result that the relaxation time of the particle to adjust to local tangential velocity of gas is of the order of 0.3 ms for a 10 μm particle with assumption of Stoke's drag and is expected to be much less in actual case.

Assumption (iv) implies that the density of the particles reaching the wall corresponds to char density and that the diameter of the particle keeps decreasing as the particles travel to the walls. Further, the devolatilization time is negligible compared to heating and burn up time scales under typical MHD cyclone burner conditions.

In Assumption (v) it is in fact important to define C_d and diameters by air classification rather than sieve sizing for real pulverized coal.

Assumption (vi) appears to be an oversimplification. The radial velocity of gas can either be toward the wall or towards the axis depending upon the location inside the burner. The magnitude of radial velocity of gases ($\bar{V}_r \sim 5$ m/s) is small compared to the radial velocity ($\bar{V}_r \sim 30$ m/s) imparted to the particle by the centrifugal forces and hence parametric treatment is justified.

3.2 GOVERNING EQUATIONS

3.2.1 Dimensional Form

The basic momentum equation in the radial direction is given as:
\[
\frac{\pi d_p^3}{6} \rho_p \frac{dV_r}{dt} = \rho_p \frac{\pi d_p^3}{6} \frac{V_t^3}{r^2} - \left( \frac{C_d}{2} \right) \rho_g (V_r - v_r)^2 \frac{\pi d_p^2}{4} - \frac{\pi d_p^2}{4} \frac{\partial p}{\partial r}
\]  

(3)

where

- \(d_p\), particle diameter
- \(\rho_g\), gas density

There is no necessity for a momentum conservation equation in the tangential direction in view of assumption (i) from which it follows that \(V_t = v_t\) and from relation (1) \(v_t\) is known as a function of \(r\).

The time taken to travel to the wall \(t_w\), impact time, is implicitly given by

\[
(r_w - r_i) = \int_0^{t_w} V_r \, dt
\]  

(4)

where

- \(r_w\), radius of wall
- \(r_i\), radius of injection of particle

If \(V_r\) is known as a function of \(r\), then an explicit solution can be found from

\[
t_w = \int_{r_i}^{r_w} \frac{dr}{V_r}
\]  

(4a)
Equation (3) can be transformed by choice of \( r \) as an independent variable, with \( \frac{d}{dt} = V_r \frac{d}{dr} \). Hence a solution for \( V_r \) can be obtained as a function of \( r \), with the time varying \( d_p \) defined below.

The change in particle diameter due to diffusion controlled burning is given by a diameter square law:

\[
d_{p}^2 = d_{p,0}^2 - \left( 8 \frac{Y_{\infty} \rho_g D}{v_s \rho_c} \right) [H(t-t_h)] \cdot (t-t_h)
\]

(5)

where

- \( d_{p,0} \), particle diameter at \( t = 0 \)
- \( \rho_c \), density of char
- \( Y_{\infty} \), free stream concentration of reacting gas which can be \( O_2 \), \( CO_2 \), etc.
- \( v_s \), stoichiometric consumption of reacting gas per unit mass of char
- \( D \), diffusion coefficient
- \( t_h \), time to heat up the particle to diffusion controlled reaction temperature

\[ H(t-t_h), \text{ Heavy side function} \]

\[ = 0 \quad t < t_h \]

\[ = 1 \quad t > t_h \]

For Eq. (5) it is assumed that the mineral matter is concentrated at the center and as such is small compared to the diameter of the original coal particle.

The burning time can be calculated from Eq. (5) by setting \( d_p = 0 \)

\[
t_b = d_{p,0}^2 \left( \frac{v_s \rho_c}{8Y_{\infty} \rho_g D} \right) \frac{2\sqrt{t}}{d_p},
\]

(5a)
The characteristic heating time of the particle for the convective/conductive heat transfer mode is given with radiative transport assumed relatively unimportant in this regime, as

\[
  t_h = \frac{\rho_p C_{p,p} d_p \kappa^2}{6 N_u \lambda}
\]

(5b)

where

- \( C_{p,p} \), specific heat of particle
- \( N_u \), Nusselt number, \( = (2 + 0.6 Re^{1/2}) \), \( R_e = \frac{V d_p}{\nu} \)
- \( \lambda \), thermal conductivity of gas

\( = 2 \) for quiescent gas

3.2.2 Nondimensional Form

Let

\[
  V_{ref} = V_t r_{I,g} / r_w
\]

\[
  t_{ref} = r_w / V_{ref}
\]

\[
  R = r / r_w
\]

\[
  \tau = t / t_{ref}
\]

\[
  V^+ = V / V_{ref}
\]

\[
  d_{p,\text{ref}} = \left\{ 3 A_{\nu} \nu r_w \rho_g V_{ref}^{-m} \right\}^{1/(1+m)}
\]

\[
  \beta = \frac{(d_{p,\text{ref}}/d_p)^{1+m}}{1+m}
\]
where \( r_{I,g} \), radius of gas injection to the combustor. The parameter \( \beta \) is physically a comparison of frictional force with inertial force. Introducing Eqs. (6) in Eq. (3), one obtains for the case without burning

\[
\frac{d^2 R}{d\tau^2} = \frac{2}{R(2^2 + 1)} - \beta \left[ \frac{dR}{d\tau} - v_r^+ \right]^{2-m}
\]

and the impact time is implicitly given as

\[
\int_{R_I}^{1.0} \frac{dr}{(dR/d\tau)} = w
\]

For the case with burning during travel to the wall, Eq. (7) is still valid with \( \beta \) as a function of \( S \) as given below.

\[
\beta = \beta_0 \left(1 - S\right)^{-\left(1+m\right)/2}
\]

where \( \beta_0 \) is same as \( \beta \) with \( d_p \) replaced by \( d_{p,0} \)

\[
S = \left[ \gamma_b - \tau \beta^{2/\left(1+m\right)} - \gamma_h \right], \quad S > 0
\]

\[
\gamma_b = \frac{8Y_\infty \rho D r_w d_{p,ref}^2}{\nu s_{p,ref}}
\]

\[
\gamma_h = \frac{\rho_p c_p, p V_{ref}}{6 \ Nu \ \lambda r_w d_{p,ref}^2}
\]
Substituting Eq. (9) in Eq. (7) the governing equation for the radial motion of the particle with burning is given as

$$\frac{d^2R}{dt^2} = \frac{2}{R(2\xi + 1)} - \theta_0 \left[ \frac{dR}{dt} - v_r^+ \right]^{2-m} (1 - S)^{-(1+m)/2}$$

(11)

Solution of Eqs. (7) and (11) can be numerically obtained. It will be seen later that the solution of Eq. (11) with burning does not yield significantly different results from the solution of Eq. (7) as far as slag rejection is concerned. This vault does implicitly assume that mineral vaporization is not significant during particle burning.

4.0 RESULTS AND DISCUSSION

Slag rejection is interpreted in terms of relative phenomenological time scales. To achieve wall impact of a specific initial particle size, it is required that the time from injection to impact is less than (i) particle burnup time, and (ii) combustor residence time.

Equations (3) and (4) can be solved numerically to obtain the results for time to reach wall for given geometry and operating conditions of cyclone burner. A few simple explicit results for $\tau_w$ are given in Appendix A for the cases of (i) forced vortex flow ($\zeta = -1$ in Eq. (1)) and Stoke's drag, ($m = 1$ in Eq. (2)) and (ii) forced vortex flow and constant friction coefficient. Further, explicit results for the radial velocity of particles are also shown in the Appendix for both the previous cases and in addition for the case of free vortex flow ($\zeta = 1$ in Eq. (1)) and flow with $\zeta = 1/2$ which approximately accounts for the viscous effects of the flow. From the results for radial velocity of the particle, one can also obtain the velocity with which the particles impinge on the slag layer of the wall. Numerical results for impact time to reach the wall and its relevance to slag rejection will be discussed in detail.

The numerical results will be discussed for 1) $v_r = 0$ and 2) $v_r \neq 0$. 

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4.1 NEGLIGIBLE RADIAL GAS VELOCITY AND CHAR BURNING

Figure 4 shows the results for nondimension time $\tau$ (left hand ordinate) versus coal injector position $R_I$ with $\beta$ (ratio of frictional to inertial force) as a parameter. Increasing values of $\beta$ indicate large frictional force or small inertial force (i.e., small particle diameter) which decreases the radial velocity of particles, thus increasing the travel time to reach wall. The nondimensional time has been converted to dimensional form using the constants listed in Table 3 and the definitions listed in Section 3.2. For the burner under consideration with $d_p = 10 \, \mu m$, $\beta \sim 100$ and $\beta \propto d_p^{-1.625}$.

When the particle size is large, the time to reach wall reaches a peak (see curve ABC for $\beta = 20$) at some radius of injection. The reason is that particles injected at $R_I = 0.10$ with zero radial velocity have attained a high radial velocity by the time they reach $R \sim 0.4$ while the particles injected at $R_I = 0.4$ have zero radial velocity assigned. The travel time over the radial distance, $0.1 < R_I < 0.4$ is less than the radial acceleration time starting at $R_I = 0.4$. For increasing $\beta$ (decreasing particle size) such a peak almost disappears due to large drag force (or small inertial force) which decreases the radial velocity. Then using Figure 3 for various values of $\beta$ (i.e., for various values of $d_p$), one can obtain $t_w$ versus $d_p$ and draw the curve CQPQ in Figure 5.

If the particles burn up within the free flight time prior to impact (impact time), then only ash remains and the remaining ash is believed to break up into three to five particles.\(^{(6)}\) Thus a typical ash particle diameter reduces to one-fifth of the original diameter for a coal particle of about 15 percent ash content on the presumption that ash from each coal particle comes to about 15 \, \mu m. Most particles of this size and smaller will be either vaporized before imparting the wall or entrained in the gas flow. Hence, most of this ash is lost to the gas phase. Thus, from the point of view of ash rejection to wall, the particle burnup time scale is important relative to the travel time. For simplicity, it is assumed that no ash vaporization occurs during particle combustion.

The total burning time scale is a sum of (i) mixing, (ii) heating, (iii) pyrolysis, and (iv) char burning time scales. The mixing time scale is estimated to be about 1 ms and heating time scale is of the order of 10 ms for
Figure 4. Particle Travel Time to Wall vs Coal Injector Position
TABLE 3. BURNER GEOMETRY, OPERATING CONDITIONS AND OTHER PROPERTIES

Tangential Velocity (at Injection Point) \( V_t = 1.0 \times 10^4 \text{ cm/s} \)

Cyclone Radius \( r_w = 20 \text{ cm} \)

Coal Injection Radius \( r_i = 15 \text{ cm} \)

Length of Cyclone \( L = 58 \text{ cm} \)

Pressure \( P = 2.75 \text{ atm} \)

Radial (Inward) Velocity \( v_r = 0.25 V_t \)

Oxygen Concentration \( Y_{O_2} = 0.50 \)

Stoichiometric Oxygen \( v_s = 1.33 \)

Kinematic Viscosity \( \nu = 2 \text{ cm}^2/\text{s (at 1 atm)} \)

Mass Diffusion Rate \( \rho D = 7 \times 10^{-4} \text{ g/cm-s (at 1 atm)} \)

Friction Coefficient \( C_f/2 = A/Re^m \)

Gas Density at Atm. Pressure \( \rho_g = 1 \times 10^{-4} \text{ g/cm}^3 \)

Particle Density \( \rho_p = 1 \text{ g/cc} \)

Char Density \( \rho_c = 0.5 \text{ g/cc} \)

Specific Heat of Char \( c_{p_c} = 1.2 \text{ J/gK} \)

Average Residence Time for Particle \( \tau_R = 40 \text{ ms} \)

Thermal Conductivity of Gas \( \lambda = 10^{-3} \text{ W/cmK} \)

Heat of Combustion \( \Delta h_c = 9208 \text{ J/g of carbon} \)

Char Emissivity \( \varepsilon = 1.0 \)

Slag Temperature \( T_s = 1800 \text{ K} \)

Specific Heat of Gas \( c_p = 2.4 \text{ J/gK} \)

Stefan – Boltzmann \( \sigma = 5.67 \times 10^{-12} \text{ W/cm}^2 \text{ K}^4 \)

\( \text{Coal flow} \sim 24 \text{ kg/s} \)

\( \text{Si, Mn flow} \sim 0.08 \text{ kg/s} \)

\( \text{Oxidizer Flow} \sim 0.6 \text{ kg/s} \)
a 100 μm particle. The characteristic pyrolysis time scale is of the order of 2-3 ms at a particle temperature \( T_p \sim 1300 \text{ K} \). The burning time scale under diffusion controlled burning is of the order of 30 ms for \( d_p = 100 \mu m \). Thus, as discussed above, the two most important time scales are heating and char burning times, both of which are proportional to the square of particle diameter.

The total heat up and the burnup time scale versus diameter is plotted in Figure 5 (line APB). For \( d_p < 25 \mu m \), the burnup time scale \( t_b \) is less than \( t_w \), which is shown for various bulk flow conditions. Thus the particles will be burnt before they reach the wall, and their initial ash content will be entrained in the gas phase. There is also plotted the available residence time scale \( t_{res} \) in the cyclone (line EF). The residence time has been calculated as follows:

\[
    t_{res} = \frac{m}{\dot{m}}
\]

(12)

where

- \( m \), mass in cyclone at product gas density
- \( \dot{m} \), gas flow rate into cyclone.

The residence time with the present assumption is independent of particle size. The residence time line intersects the travel time line at \( Q \). According to this analysis, particles below about 2 μm never reach wall within the available residence time, while particles smaller than 25 μm combust completely before wall impact.

*The residence time line is above the intersection point \( P \) (Figure 5) since under MHD cyclone combustor conditions, with enriched oxygen and increased transport coefficient to the particles, the time to burn is small. Also line CD may be shifted upwards if free vortex law is not followed. Hence, depending upon the design and operating conditions of cyclone, the intersection point \( Q \) may be above or below point \( P \).*
These results are based on the assumption that angular momentum of gas is conserved. However, the gas supplies rotational momentum to the particles and some momentum is lost because of wall friction. Also, gas turbulent exchange is typically significant. Hence, a free vortex flow law is not followed. Thus, with viscous effects, $x \sim 0.5$ (cf. Eq. (1)) and curve $C_{1}D_{1}$ in Figure 5 corresponds to this case. The shift in the intersection point of the initial separation and burning time curves (from $P$ to $P_{1}$) is not significant.

4.2 CONSTANT GAS RADIAL VELOCITY AND NEGLIGIBLE BURNING

The gas injected at the wall has to escape through the re-entrant throat. Moreover, the gas itself is given an inward radial motion at the entry. Consistent with assumption (v), we will assume a constant radial velocity. If it is idealized that the gas has to travel from the wall to the center of cyclone within the available residence time ($\sim 40$ ms) then a limiting estimation can be made for the radial velocity. Such an estimate yields $V_{r} = 5$ m/s while tangential velocity $V_{t} = 100$ m/s. In Figure 5, curve $C_{2}D_{2}$ shows the effect of gas radial velocity. The inward radial velocity of gas gives a higher travel time scale (line $C_{2}D_{2}$). Such a curve intersects the burn time line at $P_{2}$ giving a particle size limit of about 26 $\mu$m for wall capture. The effect on particle travel time scale is significant. The particles accelerate to a high radial velocity due to centrifugal force. Since $V_{r} \sim 5$ m/s while initial $V_{r} \sim 100$ m/s, the drag force is mostly due to particle velocity. As the particles approach the wall, the centrifugal force drops down due to decreasing tangential velocity of gas. Further, the particle radial velocity is slowed down due to the drag force. A point is reached at which centrifugal force is equal to the drag force at which the particle velocity is maximum. Further approach to the wall results in less centrifugal force and dominant drag force both due to inward flowing gases and particle velocity. The resulting lower radial velocity of the particle increases the time scale to reach the wall. For certain particle sizes $d_{p} < d_{p, crit}$, $V_{r} = 0$ at $r = r_{crit} < r_{w}$ and these particles revolve around at a fixed orbit never reaching the wall. Such a size is given by letting $d^{2}R/dt^{2} = 0$ and $dR/d = 0$ in Eq. (7).
\[ \beta_{\text{crit}} = 2 \left( \frac{v_{\text{ref}}}{v_r} \right)^{2-m} \frac{1}{R(2\xi + 1)} \] (13)

Thus with \( v_r = 0.05 \, V_t \), \( R = V_t \) and since \( \beta = d_p^{1.625} \) and \( \beta = 100 \) for \( d_p = 10 \, \mu m \), one can get \( d_{p,\text{crit}} = 9 \, \mu m \). According to this analysis, the particles having size below 9 \( \mu m \) will eventually be entrained by the gas streams.

Referring to Figure 5 it is seen that particles having \( d_p \) less than about 30 \( \mu m \) will be burnt, and their mineral matter evaporated, prior to reaching wall. From Figure 3, it is observed that there is about 60 percent of mass having particle size below 30 \( \mu m \) for Illinois No. 6 coal while for Polish coal, it is only 30 percent. As for Illinois No. 6 coal, 60 percent of mass is burnt in the gas phase and only 40 percent is deposited inertially on the wall. Consequently at most about 40 percent of coal ash is collected as slag with the Illinois No. 6 grind while up to 10 percent could be recovered for the Polish Bytom grind. This is consistent with the experimental results given in Table 2.

4.3 EFFECTS OF BURNING

Under diffusion controlled burning with constant density, the particle diameter keeps decreasing while the particle is traveling towards the wall, which results in increased drag force per unit mass. Numerical results including this effect were obtained. In this case, even though initial particle diameter is larger than 30 \( \mu m \), the particle may reach a size much less than 30 \( \mu m \) by the time it reaches the wall. Consequently the above results are optimistic in terms of ash capture. The results obtained including burning effects suggested that there is about a 10 percent increase in transition size of the particle for capture prior to burnout.
5.0 SCALING LAWS

Because of the nondimensional nature of derivations one can present a few scaling relations with regards to the effects of geometry, operating variables, fuel types and particle size on slag rejection in cyclone burners. It is of interest to know the article size below which the particles will be entrained by the gases. Such a size can be obtained from Figure 5 where time scales $t_w$, $t_b$ and $t_{res}$ were plotted against $d_p$.

Figure 6 gives a plot of nondimensional time $\tau_w$ versus $\beta$ for the coal injector position $R_I = 0.75$.

$$\tau_w \approx 0.128 \beta^{0.7}$$

(14)

Using the definition for $\tau_w$ one can show that

$$t_w = \frac{r_w \beta^{0.7}}{V_{ref}}$$

(15)

Using the definition for $\beta$

$$t_w = \frac{r_w}{V_t^{1.3}} \cdot \frac{p^{0.3}}{d_p^{1.2}} \cdot \frac{r^{1.3}}{g,I}$$

(16)

From diffusion controlled burning theory,

$$t_b = \frac{d_p^2}{V_{\infty}}$$

(17)

The gas residence time for constant $L/r_w$ scales as

$$t_{res} \propto Pr_{rw}$$

(18)
Figure 6. Nondimensional Impact Time Dependence on Nondimensional Drag Force

\[ \tau = 0.128 \beta^{0.702} \]

\[ v_f = 0, \quad \beta = 1. \]
Where $P$ is the pressure of operation of the burner. For conditions such that

i) $t_w/t_b > 1.0$ or

ii) $t_w/t_{res} > 1.0$

no ash will be rejected on the wall. For the present MHD burner, condition (i) applies.

Thus the condition

$$t_w/t_b > 1$$

implies that the following group

$$G = 2.2 \left( \frac{v_0^3 \rho_{g0}}{\rho_c v_t^{1.3}} \right) \frac{r_w^{1.7}}{d_p^{3.2}} \frac{1.7 p^{0.3}}{t_{g1}} Y_{\infty} > 1$$

(19)

for the zero ash capture break point, where $v_0$, $\rho_{g0}$ are the properties evaluated at pressure $P = 1$ atm. Increasing value of $G$ implies decreased ash rejection. The dominant operational parameter appears to be the particle size. Note that a lesser concentration of $Y_{\infty}$ (in a richer environment) as in a two-stage cyclone enhances slag rejection due to increased burning times of particles relative to transport time to wall, as well as a lower bulk temperature driving ash vaporization.

The time scales so far obtained for $t_w$ presumes that gas is injected tangentially at the walls. However, the center line of the secondary air jet is at a radius of 17.7 cm while the cyclone radius is 20 cm.

* If residence time $t_{res}$ falls below intersection point $P$, a different law exists. All the article sizes below point $Q_3$ will be burned, particles having size $d_{p,3} < d_p < d_{p,4}$ will escape unburned. Ash will be lost for all particles having size below $d_{p,4}$. Consequently, one should keep $t_{res}$ above $P$. 

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Further at entry the coal:air jet is not swirling (coal + primary air mass \( \approx 0.3 \)), at the same velocity as gas; hence, the tangential velocity of the whole air and coal must be reduced approximately to a factor of 0.7. Combining the effects of reduction in tangential velocity and the radius of injection, it can be shown using the scaling group that the time to travel to the wall \( t_w \) is increased by a factor of two. Correspondingly, the transition size (size below which impact time is shorter than burning time) will be increased to about 30 \( \mu m \). This is given in Figure 5 as \( C_3 D_3 \).

6.0 SUMMARY

- The low ash rejection with Illinois No. 6 coal is the result of finer particle size in the feed compared to the size of Polish coals. From the analysis; it is shown that in order to maximize slag deposition on the cyclone walls the feed must have negligible mass in the size range below 30 \( \mu m \).

- A secondary effect of low ash rejection at the walls is a nonuniform and insufficient thickness of the slag layer. A consequence of this may be to further reduce slag rejection as the thin, low humidity slag layer may not be effective in capturing large impinging char particles.

- Coal injector position does not significantly affect the time to reach wall for a position up to about 70 percent of the radius of the cyclone; but, the location at which the secondary gas input is introduced into the cyclone affects the impact time significantly.

- When air is staged so as to maintain a fuel rich environment as long as possible the slag capture efficiency is improved.

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APPENDIX A

SIMPLE SOLUTION FOR A FEW SPECIFIC CASES

1. FORCED VORTEX AND CONSTANT FRICTION COEFFICIENT

For forced vortex $k = -1$ and if we assume $m = 0$, $v_\tau^* = 0$, then

$$\frac{dz}{dR} = 2R - \beta Z$$ \hspace{1cm} (A-1)

where

$$Z = (v_\tau^*)^2$$

$$\beta = \{3A r w \rho g / \rho c \}^{1 + \infty}$$

After integration,

$$Z = \int_{0}^{R-R_B} 2(R - \eta) e^{-\beta \eta} d\eta$$ \hspace{1cm} (A-2)

$$= \left[ R + \frac{(1-R_B)}{\beta} \right] e^{-\beta (R-R_B)} - \frac{1}{\beta}$$

If $\beta >> 1$, $R > R_B$

$$Z \sim (R - \frac{1}{\beta})$$

Using Eq. (8) in Section 3.22,

$$C = \int_{R_1}^{R} \frac{dR}{\sqrt{Z}}$$
With approximate result for \( \tau \)

\[
\tau \sim \sqrt{2\beta} \left\{ \sqrt{R - \frac{1}{\beta}} - \sqrt{R_I - \frac{1}{\beta}} \right\}
\]  

(A-3)

2. FORCED VORTEX AND STOKE'S DRAG

For Stoke's drag, \( \lambda = -1 \) (forced vortex flow), \( m = 1/2 \) \( A \approx 12 \).

\[
\mathcal{D} \frac{d^2 R}{d\tau^2} + \frac{\beta dR}{d\tau} - 2R = 0
\]  

(A-4)

Integrating, \( R \) as a function of \( \tau \) can be obtained

\[
\frac{R}{R_I} = \frac{1}{2} \left( 1 + \beta/2 \sqrt{1 + \beta^2/4} \right) \exp \left\{ [\frac{\beta}{2} + \beta^2/4] \frac{\tau}{2} \right\}
\]

\[
+ \frac{1}{2} \left( 1 - \beta/2 \sqrt{1 + \beta^2/4} \right) \exp \left\{ [-\beta/2 + \beta^2/4] \frac{\tau}{2} \right\}
\]  

(A-5)

with \( R = 1, \tau \) can be estimated as a function of time with \( R_I \) as an independent variable and \( \beta \) as a parameter. \( \tau_{\text{for}} \sim \frac{R}{R_I} \sim \exp \left( \frac{2\tau}{\beta} \right) \)