Blast furnace gas cleaning system design

A cyclone dust catcher followed by an annular gap scrubber offers a number of distinct advantages to blast furnace operators. These include high dust removal efficiency and minimal sludge handling. The low pressure drop requirement makes the system especially suited for installations for low top pressure furnaces, as well as for those with top gas energy recovery turbines, and a very low water requirement helps minimise energy consumption.

Dry separation of dust particles in the blast furnace top gas before wet scrubbing is commonly done by a gravity dustcatcher or most recently by large diameter cyclones (see Figure 1). The objective is to remove as much dust as possible in a dry condition for reuse and recycling. The recycled dust must also be low in Zn and Pb to satisfy the limits of the blast furnace zinc balance. The dust removal efficiency of any separator is dependent on the particle size distribution, on the separation mechanism (i.e., gravitational or centrifugal force) and, to a lesser degree, on the inlet dust loading (see Table 1).

Typical inlet dust loading is in the range 15-20gNm⁻³ of gas. The separated dust is collected in the dust storage hopper, which is usually sized for 1½ days of dust accumulation, and emptied via an automatic dust discharge system into sealed containers for transport to the recycling facility.

GRAVITY DUSTCATCHER
The operation and efficiency of a conventional gravity dustcatcher are governed by Stokes’ Law. In 1851, George Stokes derived an expression for the frictional force (also called drag force) exerted on spherical objects with very small Reynolds (Re) numbers, e.g., very small particles, in a continuous viscous fluid by solving the small fluid-mass limit of the generally unsolvable Navier-Stokes equations. However, Stokes’ Law is only applicable to spherical objects with very small Re numbers with settling velocities in the laminar region. For particles with Re numbers higher than 0.2 and up to 100,000, the degree of turbulence becomes significant, leading to additional drag force. Hence, the settling, or terminal, velocity will be lower than that predicted by Stokes’ Law. For these particle sizes, the terminal velocity is determined by the correlation between the particle Re number and its drag coefficient using the values given in the Haywood Tables. Alternatively, the correlation between the particle Re and the Archimedes (Ar) number (valid between Re = 0.2 and 20,000) can be used.

Table 1 Typical particle size distribution

<table>
<thead>
<tr>
<th>Class</th>
<th>Particle size, µm</th>
<th>Mean size, µm</th>
<th>Distribution, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-10</td>
<td>5</td>
<td>9.5</td>
</tr>
<tr>
<td>2</td>
<td>11-20</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>21-40</td>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>41-80</td>
<td>60</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>81-120</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>121-200</td>
<td>160</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>201-300</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>301-600</td>
<td>450</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 1 Typical BF dust removal system
Table 1 Typical particle size distribution
If the particles are falling in a viscous fluid by their own weight, then a terminal velocity, also known as the settling velocity, is reached when this frictional force combined with the buoyant force exactly balance the gravitational force. Based on the combined Stokes’ Law and Haywood Tables, the terminal velocity of each group of particles can be determined (see Figure 2). From the particle terminal velocity the removal efficiency can be calculated, which is dependent on the ascending gas velocity in the dustcatcher annulus and, hence, the barrel diameter (see Figure 3).

**CYCLONE DUSTCATCHER**

Unlike a gravity dustcatcher the operation and efficiency of a cyclone dustcatcher is based on centrifugal forces. In the Danieli Corus cyclone the gas is introduced by one or two tangential inlets with a velocity to force the dust particles to the wall and separate them from the gas stream (see Figure 4). This type of cyclone is completely empty, without a complicated inlet dome and replaceable guide vanes, and thus costs of construction and maintenance are greatly reduced. The cyclone comes complete with vortex finder, apex, flow cone and a dust collection hopper with a bifurcated pant-leg type dual dust outlet.

The collection efficiency of the cyclone depends very much on particle size distribution. Particles below 5μm are not removed due to their small mass; particles between 5μm and 30μm are partially separated and particles larger than 30μm are separated with almost 100% efficiency (see Figures 5 & 6). Overall separation efficiency of 85% or better can be achieved and the removed dry dust, containing very little Zn and Pb concentrations, is readily recycled.

The amount of sludge produced in the wet scrubbing stage is thus greatly reduced and since Zn and Pb are concentrated in the sludge, with about 75% of the Zn and 79% of the Pb found in the particles of less than 5μm, the secondary treatment by hydro-cyclonage is not required. This is illustrated in Table 2.

**DUST DISCHARGE SYSTEM**

The dust discharge system is based on use of two intermediate dust collection tanks in parallel below the dust collection hopper outlet nozzles. The tanks are designed to dump dust on a batch basis below near-atmospheric pressure to prevent dust build-up in the dustcatcher or cyclone and to reduce dust and gas emissions. This is accomplished by two inflatable seal dome valves installed at the inlet and outlet of the dust collection tanks. The tanks empty into pugmills where the dust is wetted before it is discharged onto the ground or directly into a sealed container below.

Two radar-type level sensing devices are installed in the dust hopper for level indication. Signals from the level sensing devices are used to monitor dust build-up, initiate dust dump cycle and provide low and high level alarms.
In automatic mode, the dust discharge system is controlled via the gas cleaning plant PLC. When a cycle is initiated, the pressurising valve opens and nitrogen is admitted into the dust collection tank through a small pressurising cyclone. Simultaneously, the valve at the bottom of the pressurising cyclone opens, allowing the dust collected in the cyclone during de-pressurisation to be blown back into the dust collection tank. A typical dust discharge computer screen is shown in Figure 7.

After pressure equalisation between the cyclone and the dust collection tank, the fill valve is opened. The valve will be closed on the ‘tank full’ signal or after a predetermined time period. When the fill valve is confirmed closed, the depressurising valve will be opened and the pressurised gas vented into the clean gas main through the pressurising cyclone. At completion of de-pressurisation the dust collection tank discharge valve is opened to empty the dust into the pug mill. The valve will be closed on the ‘tank empty’ indication or after a predetermined time period.

The system cycle period can be determined according

<table>
<thead>
<tr>
<th>Dust removal by</th>
<th>Dustcatcher</th>
<th>Cyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry dust → zinc poor</td>
<td>50%</td>
<td>85% → recycle</td>
</tr>
<tr>
<td>Sludge → zinc poor</td>
<td>35%</td>
<td>15% → recycle</td>
</tr>
<tr>
<td>Sludge → zinc rich</td>
<td>15%</td>
<td>15% → storage</td>
</tr>
</tbody>
</table>

**Example**

<table>
<thead>
<tr>
<th></th>
<th>Dustcatcher</th>
<th>Cyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top gas flow (Nm³/h)</td>
<td>500,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Dust Content (g/Nm³)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>50</td>
<td>85</td>
</tr>
<tr>
<td>Dust captured (kg/h)</td>
<td>3,000</td>
<td>5,100</td>
</tr>
<tr>
<td>Sludge to be treated (kg/h)</td>
<td>3,000</td>
<td>900</td>
</tr>
</tbody>
</table>

Table 2 Comparison between dustcatchers and cyclones

**Fig 5** Modelled behaviour of 5μm and 30μm particles

**Fig 6** Relationship between particle size and removal efficiency
to theoretical dust accumulation. Actual dust hopper level signals can be used to initiate a discharge cycle according to production, or to interrupt a predetermined time cycle. This way, overfilling or accidental gas discharge is prevented.

**WET SEPARATION OF DUST**

Trouble-free scrubber operation, even during rough furnace driving conditions, is a prerequisite to economical iron production. The design of the Bischoff annular gap scrubber has been fully optimised through experience gained in more than 100 installations worldwide to provide high reliability and superior performance. The single tower construction comprises the pre-scrubber/cooler and the annular gap scrubber stages, and is followed by a high-efficiency, external moisture separator.

The characteristics of the annular gap scrubber are:
- Multiple dust removal mechanisms
- Minimum scrubbing water requirements
- Superior top pressure control
- Proven performance and high efficiency

Because of its unique design, the annular gap scrubber also offers the least space requirement along with the lowest energy consumption and the lowest noise emission.

**DUST REMOVAL MECHANISMS**

The separation of dust particles from the blast furnace gas requires the application of a force that produces differential motion of the particle relative to the gas and sufficient retention time for the particle to migrate to the collecting surface. The principal separating mechanisms (see Figures 8 & 9) in an annular gap scrubber are:
- Inertial interception
- Turbulent (Brownian) diffusion
- Flow line interception

Inertial interception is characterised by the different inertial forces of the varying masses. When the dust-laden gas flows around the collecting water droplet, the dust particles of larger mass do not follow the flow lines of the gas stream. These particles, propelled by the inertia force, strike and penetrate the water droplet, and thus are removed from the gas stream.

Turbulent diffusion is highly effective in removing smaller dust particles from the gas stream. Small particles, particularly those below about 0.3μm in diameter, exhibit considerable Brownian movement and do not move uniformly along the gas streamline. These particles diffuse from the gas stream to the surface of the water droplets and are collected. This collection mechanism can only function in scrubbers that promote turbulent flow of a gas-liquid mixture, operate at low velocity and provide sufficient retention time.
Flow-line interception only functions if the gas streamline passes within one particle radius of the collecting water droplet. The dust particle travelling along this streamline will touch the water droplet and will be collected without the influence of inertia, or turbulent diffusion.

WATER REQUIREMENTS
After primary separation in the dustcatcher, or cyclone, the blast furnace top gas is scrubbed with water in the annular gap scrubber to obtain the desired residual clean gas particulate concentration. The quantity of water required for scrubbing is relatively low and thus the gas cooling requirements normally determine the total water flow rate. The water circuits are optimised through internal water recirculation to minimise the capacity of the recycle system. For example, to cool the top gas from 150°C to 38°C, 3.0 l/Nm³ water at a temperature of 30°C is required when the furnace is operated at 2.5 bar top pressure.

The relationship between gas temperature and water flow rate is shown in Figure 10. Normally, clean gas temperatures of 35-40°C are desirable, to minimise water vapour in the gas. If a top gas recovery turbine (TRT) is in operation, it is desirable to keep the gas temperature high and thus maximise the enthalpy gradient that can be converted to useful energy. This enthalpy gradient, for a given inlet and outlet pressure, is directly proportional to the turbine inlet temperature.

Therefore, under normal conditions and to achieve a clean gas temperature of 35-40°C downstream of the turbine, the top gas is cooled to 50-60°C. The adiabatic expansion of the gas across the turbine provides the additional cooling. Cooling of the top gas to 50-60°C is achieved by reduced cooling water flow, or bypassing the cooling tower of the recycle system. As in the previous example, if a TRT inlet gas temperature of 50°C is to be maintained, the total scrubbing water requirements are reduced to 1.4 l/Nm³.

PERFORMANCE
The performance of a blast furnace gas cleaning system is generally evaluated on the basis of outlet dust concentration and moisture content (see Figures 11 & 12). The dust collection efficiency of the annular gap scrubber depends on the throat velocity or pressure drop, and the liquid-to-gas ratio. Since collecting particles of given size and mass depends on the level of energy expended, higher pressure drop across the scrubber will result in increased efficiency and lower dust outlet concentration. The best efficiency at any pressure drop is achieved with a constant liquid-to-gas ratio of approximately 0.75-1.0 l/Nm³. As indicated on the performance curve in Figure 11, a residual dust concentration of 5mg/Nm³ is achieved with relatively low pressure drop of about
200 mbar. High efficiency dust collection at low pressure drop makes the annular gap scrubber particularly suitable for installations on low top pressure blast furnaces, or high top pressure operation with top gas energy recovery turbines. On the other hand, the three parallel scrubber elements are also suitable for single stage pressure reduction when the turbine is not installed, or is out of operation. The flexibility to handle a wide range of conditions is inherent in the design of the annular gap scrubber.

The saturated moisture content of the gas is temperature dependent. In addition to water vapour the gas also carries entrained or free water droplets which are removed in the demister. High temperature with high entrained moisture reduces the calorific value of the gas and, thus higher enrichment gas rates are required for firing the stoves to maintain the desired flame temperature (see Figure 13).

Gas temperature can be controlled by the quantity of cooling water used in the cross-flow prescrubber/cooler section, while the properly sized demister limits the entrained moisture to below 5 g/Nm³.

CONCLUSIONS
A cyclone followed by an annular gap scrubber offers a number of distinct advantages:

- High dust removal efficiency of 85% or higher and to a guaranteed value of 5 mg/Nm³.
- Minimal sludge handling and treatment since Zn and Pb are concentrated in the sludge, with about 75% of the Zn and 79% of the Pb found in the particles of less than 5 μm, secondary treatment by a hydro-cyclone is not required.
- The low pressure drop requirement makes the system especially suited for installations for low top pressure furnaces as well as for installations with top gas energy recovery turbines.
- Efficient demisting limits the residual free water content in the clean gas to below 5 g/Nm³ – an important factor when used as fuel to fire the hot blast stoves and steam generating equipment.
- Minimum water requirement as the annular gap scrubber operates with a low and constant water-to-gas ratio of 0.75 l/Nm³ of gas. When gas cooling is not required, eg, in installations with top gas energy recovery turbine, the recycle water system capacity can be greatly reduced.
- Low pressure drop gas cleaning in combination with the minimum water-to-gas ratio reduces the size of the water recycle system and thus minimises energy consumption.

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