Recent developments in blast furnace operation, characterised by long campaign life combined with ever increasing productivity and high rates of fuel injection, require high efficiency top gas cleaning equipment to cope with the changes in top gas composition, dust loading, pressure and temperature fluctuations and which match the campaign life of the furnace. The advantages of the annular gap scrubber in comparison with other venturi scrubbers, include system design, operation and performance.

At Corus Ijmuiden (formerly Hoogovens) there are two blast furnaces in operation. No.6 with an 11m hearth diameter produces approximately 3Mt/yr of hot metal, while No.7 with a 13.8m hearth diameter produces approximately 4Mt/yr. Pulverised coal injection (PCI) is in excess of 200kg/t and the burden mix is 50% sinter and 50% pellets. Both blast furnaces are equipped with a dust catcher followed by a Bischoff annular gap wet scrubber, and top gas energy recovery turbine (see Figure 1).

The gas cleaning systems share a common water recycling and blow down treatment system (see Figure 2). Prior to clarification the waste water is aerated by compressed air injection in an open reactor to remove CO₂, increasing the pH from 5–6 to 7. Clarification is achieved by operating two out of three installed clarifiers. Caustic soda is added prior to the clarifier to raise the pH to 7.8 where zinc and lead solubility is at a minimum. The clarifier overflow has a suspended solids concentration of a maximum of 100mg/l and is returned to the blast furnaces without passing over a cooling tower at a temperature of 40°C.

A blow down stream of 100m³/hr is treated by two 'Dynasand' filters in series, reducing the outlet suspended solids concentration to less than 50mg/l. Dynacyclones are used to classify the thickener underflow into large and small particles. The small particle fraction, which is high in zinc, is stored in a temporary site for possible future extraction by leaching. The large particle fraction, is lower in zinc and higher in iron and is recycled to the blast furnace via the sinter plant to the extent permitted by the zinc-input restriction.

**BLAST FURNACE OPERATION**

An important by-product of the blast furnace process is blast furnace gas, used as fuel for heating blast air in the hot blast stoves and as supplemental fuel for steam and power generation. The primary function of the blast furnace gas cleaning system is to remove particulate matter from this gas. In addition, the system also cools...
the gas to reduce its moisture content, thus increasing its calorific value. The recovered sludge contains relatively high quantities of iron and carbon and can thus be recycled as, in our case, through the sinter plant.

Knowledge of the blast furnace process is necessary for the proper design and operation of the gas cleaning system. Burden preparation and type, pellet or sinter, will affect the quantity and particle size of the dust. Also, the choice and preparation of fluxing materials can affect the water chemistry in the scrubber system. Calcium can be introduced to the water system from limestone used as a fluxing agent. Coke and fuel injectants will contribute sulphur, chlorides, ammonia and nitrogen oxides. Typical gas analysis measured at two blast furnaces with PCI are given in Table 1.

Level of production and wind rates affect particulate loadings in the gas cleaning system. Top pressure and scrubber pressure drop will affect dust collection efficiency, as well as the adsorption of dissolved gases in the scrubber water.

In addition to the basic functions of cleaning and cooling of the top gas, the scrubber and/or the top gas energy recovery turbine also controls the top pressure of the blast furnace. For smooth and stable furnace operation the top pressure must be controlled and held as constant as possible. The gas cleaning system design must, therefore, be fully integrated with the operation of the blast furnace.

During operations such as charging, tapping, equalisation and change of stoves, there are inevitably variations in gas flow and pressure. The fluctuations are usually of short duration but of considerable amplitude and are felt at the top of the blast furnace as well as downstream throughout the gas system. The scrubber and/or the energy recovery turbine must be designed to handle and control such fluctuations.

**GAS CLEANING SYSTEM DESIGN**

Trouble free scrubber operation, even during rough furnace driving conditions, is a prerequisite to economic iron production. The design of the Bischoff Annular Gap scrubber has been fully optimised, through experience gained in over one hundred installations world-wide, to provide high reliability and superior performance. The single tower construction comprises the pre-scrubber/cooler and the RS, or annular gap scrubber stages, and is followed by a high efficiency, external moisture separator.

**Pre-scrubber/cooler** The pre-scrubber/cooler stage is an open vessel located in the top half of the scrubber tower. The centrally arranged spray nozzles installed on nine levels (see Figure 3) offer virtually no obstruction to the gas flow and are provided with large internal...
openings to produce a 90° hollow cone spray pattern. The nozzles are designed to spray in two directions (upwards and downwards) intercepting the adjacent nozzles’ hollow cone spray at about the middle of the vessel cross-section. In this way a fine water droplet spectrum is produced to achieve efficient cooling and particulate removal.

Almost the entire cooling as well as the removal of the coarse fractions of the blast furnace dust takes place in the pre-scrubber/cooler stage. About 80% of the raw gas dust particulate content is captured here at a negligible pressure drop of approximately 100mm (4in) water gauge.

The spray nozzles are fitted with stainless steel replaceable orifice inserts installed in the cast iron body (see Figure 4). The smallest cross-section in the body cavity is the tangential inlet of 40mm wide by 150mm high. The size of the orifice inserts’ opening varies between 40 and 65mm. These large openings ensure clog-free operation and make the nozzles insensitive to the amount of suspended solids in the recycle scrubbing water. The connection between the pre-scrubber and the raw gas main is designed to allow wetting of the transition zone between the dry-wet sections. This prevents encrustation often found in installations where the dry-wet interface constantly shifts. High lime content in the blast furnace dust and calcium carbonate-saturated scrubbing water inevitably leads to the formation of hard crusts, which can grow to considerable size, when the transition zone is not permanently wetted.

**RS-Scrubber** The RS, or annular gap scrubber is a special version of the venturi scrubber and is designed to remove the finest dust fractions. Adiabatic expansion of the gas in this stage provides additional cooling. There are normally three units installed in the lower part of the scrubber tower. These units consist of the circular gas inlet ducts, converging and diverging outer shells in which the adjustable conical RS elements are installed (see Figure 5). The asymmetric cone angles of the fixed diverging sections and the adjustable scrubber elements provide a decreasing opening in the direction of the flow and produce large changes in flow cross section with relatively small movements of the scrubber elements.

The RS elements are guided by a non-lubricated bushing and operated by hydraulic cylinders. The operating rod penetrating through the scrubber shell is supported by a lubricated bushing and is sealed by a stuffing box and grease fill. Central spray nozzles are of the same design as installed in the pre-scrubber/cooler supply scrubbing water to the RS scrubbers. An abrasion-resistant wear collar takes the impact of the water spray and the water is then guided into the scrubber throat, where it is intensively mixed with the pre-cleaned gas. Due to the long throat, long contact path and long retention time the final cleaning is achieved with low gas velocities and thus, the energy consumption of the annular gap scrubber is the lowest among the competing venturi scrubbers.

**Demister** The gas cleaning system is complete with an external mist eliminator (see Figure 6) arranged in the clean gas main immediately downstream of the scrubber vessel. Internal demisters, common in scrubbers built prior to 1982, are either not efficient enough or highly sensitive to normal swings in the quality and chemistry of the gas.
of the cleaned gas and scrubbing water. The external demister features high efficiency and is furnished with non-clogging, maintenance-free internals, designed to match the campaign life of the furnace.

**CONSTRUCTION MATERIALS**

Recent developments in blast furnace operations such as the introduction of high rates of pulverised coal and natural gas injection, and in some cases the injection of granulated plastic wastes in combination with restricted blow-down from the closed loop recyle water system, resulted in an increased concentration of chlorides and sulphites in the blast furnace gas, as well as in the recycled scrubbing water. These changes in the gas and water chemistry must be fully considered in the selection of materials and protective coatings of a wet gas cleaning system.

For example, the pre-scrubber shell is normally protected by an epoxy resin paint system and the scrubber inlet may be constructed from stainless steel, or fitted with acid-resistant tiles. The spray header pipes internal to the pre-scrubber are fabricated from stainless steel. In the RS scrubber section the circular gas inlet pipes are of stainless steel construction, while the converging and diverging outer shell and the RS element are cast from a corrosion and abrasion-resistant white iron alloy with a hardness of 600 Brinell.

All other components, such as the actuating and guide rods, guide bushing housing and stuffing box assembly are made from stainless steel.

**OPERATING CHARACTERISTICS**

The characteristics of the annular gap scrubber are best described as follows:

- Multiple dust removal mechanisms
- Minimum scrubbing water requirements
- Superior top pressure control
- Proven performance and best 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 MECHANISM**

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 in an annular gap scrubber are inertial interception, turbulent (Brownian) diffusion and flow line interception (see *Figure 7*).

**Inertial interception** is characterised by the different inertial forces of the different 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 (see Figure 8), 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 gas-liquid mixture, operate at low velocity and provide sufficient retention time.

Flow line interception only functions if the gas stream line passes within one particle radius of the collecting water droplet. The dust particle travelling along this stream line will touch the water droplet and will be collected without the influence of inertia, or turbulent diffusion.

WATER REQUIREMENTS
After primary separation in the dust catcher, 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 determines the total water flow rate. The water circuits are optimised through internal water re-circulation 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 (see Figure 9).

Normally, clean gas temperatures of 35–40°C are desirable in order 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
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 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 in combination 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 12).

Gas temperature can be controlled by the quantity of cooling water used in the cross-flow pre-scrubber/cooler section, while the properly sized demister limits the entrained moisture to below 5g/Nm³. Excessive amounts of dust and moisture are known to cause damage to and shorten the campaign life of the hot blast stoves, boilers and top gas energy recovery turbines.

Top pressure control The annular gap scrubber is not only a highly efficient dust collection device, but also provides superior top pressure control. The pressure at the furnace top is kept constant by the scrubber elements, operated via hydraulic cylinders, or by the top gas energy recovery turbine. When the turbine is in operation, the scrubber is switched to differential pressure control mode to maintain the required gas cleaning efficiency.

The scrubber and turbine are installed to operate in series with the blast furnace, but the turbine is arranged in parallel with the clean gas main (see Figure 13). For safety reasons a quick acting valve is located in the turbine supply main to close within one to two seconds of turbine failure.

The main shut-off valve then opens automatically but is controlled to ensure that pressure at the furnace top remains as constant as possible. Simultaneously, the top pressure control function carried out by the turbine inlet valve, or by variable stator blades, is switched back to the annular gap scrubber.

During normal start-up and shut-down of the turbine the changeover is smooth enough to avoid pressure variations at the furnace top and in the clean gas main. In the event of an emergency stop of the turbine, top pressure fluctuations cannot be fully avoided but are kept at low amplitudes and of short duration.

Should the main shut-off valve not open in case of emergency, the by-pass control valve, which normally becomes operative when the capacity of the turbine is exceeded, provides additional safety.
COMPARISON OF SCRUBBERS

In comparison with the short rectangular (or square) throat, variable flap venturi scrubbers the annular gap design exhibits major advantages and superior performance as outlined below.

Construction Flap venturi scrubbers, whether utilising the flooded wall approach or the gap/coverage theory, are designed with relatively short throat and water injection nozzles that are often equipped with special cleaning devices. The water jets in these high-energy scrubbers are deflected by the high velocity gas flow before reaching the centre of the throat. On the other hand, the water injected by the single non-clogging spray is guided into the throat of the annular gap scrubber where it is intensively mixed with the gas. The long and narrowing annular gap allows the scrubber to operate at relatively low gas velocities since the coarse dust particles are removed in the throat by inertial interception and the finer fractions are captured by turbulent diffusion.

Dust removal mechanism The short throat, high energy, flap venturi scrubbers rely primarily on the inertia force as the only mechanism of dust removal. The water droplets injected into the throat, using either thin jets under high pressure or thick jets under low pressure, are deflected and quickly accelerated by the high velocity gas flow, thereby limiting the path available for inertial interception. High gas velocities in the throat retard homogeneous liquid distribution and, thus reduce dust removal efficiency.

In the annular gap scrubber the atomised water is guided into the throat where it is intensively mixed with the gas. The long contact path and long retention time in the annular gap allows the scrubber to operate at relatively low gas velocities since the coarse dust particles are removed in the throat by inertial interception and the finer fractions are captured by turbulent diffusion.

Water-to-gas ratio and efficiency The short throat, high energy, flap venturi scrubbers normally require a water-to-gas ratio of 2–5 l/Nm³ for maximum dust removal efficiency. The specific water flow rate increases with the increase of differential pressure across the scrubber (see Figure 15). High differential pressure means high velocity and, hence the increase in specific water flow rate is to optimise the distribution of water droplets in the throat. The water-to-gas ratio in the annular gap scrubber is 0.75–1 l/Nm³ and does not change with increasing differential pressures (see Figure 16). The long contact path promotes complete mixing of gas and water, even at increased gas velocities.

Pressure drop The total pressure drop in any scrubber is described by the empirical formula developed by Hesketh:

\[ \Delta p = \left( \frac{v^2 \sigma A^{0.133} L^{0.78}}{C} \right) \]

Where:

- \( \Delta p \) = pressure drop
- \( v \) = gas velocity in the throat (m/s)
- \( \sigma \) = gas density (kg/m³)
- \( A \) = throat area (m²)
L = liquid-to-gas ratio (l/m³)
C = empirical constant

This constant greatly simplifies the equation by replacing other factors associated with the pressure losses due to inertia contact, liquid acceleration, the effect of the diffuser and so on. The pressure drop, or energy used for cleaning the gas is due to the inertial contact between water droplets and gas dust particles, and is the same for any scrubber system. The total energy consumption, however, accrues from the sum of pressure losses, which depend largely on the scrubber type and construction. At a given inlet gas condition, the scrubber that operates with lower throat velocities and lower liquid-to-gas ratio will require less energy to clean the gas (see Figure 17).

**Performance** The performance of a scrubber is described as the relationship between the energy expended and the achieved residual dust concentration. Cleaned gas residual dust concentration of 5mg/Nm³ (dry) is attainable with the annular gap scrubber at a pressure drop of approximately 200mbar. In comparison, the achievable gas cleanliness with a flap venturi scrubber operated at the same pressure drop ranges between 15 and 22mg/Nm³ (see Figure 18).
CONCLUSIONS

In comparison with other designs, the annular gap scrubber, proven in over 100 installations worldwide, offers distinct advantages as follows:

**High dust removal efficiency** Clean gas dust concentration of 5mg/Nm³ is guaranteed. In fact, many installations consistently achieve a gas cleanliness of between 1 and 3mg/Nm³ measured on a dry gas basis.

**Low pressure drop** The above efficiency is related to a minimum pressure drop of 200mbar measured across the annular gap. Pre-cleaning requires a pressure drop of 10mbar and the demister operates at a pressure drop of 20mbar. The total energy expended for cleaning, thus, equates to 230mbar. This low pressure drop requirement makes the annular gap scrubber especially suited for installations at low top pressure furnaces as well as for installations with top gas energy recovery turbines. On the other hand, the scrubber can also handle single stage pressure reduction from high top gas pressure to the required pressure in the work’s clean gas distribution system.

**Efficient demisting** The proprietary in-line demister limits the residual free water content in the clean gas to below 5g/Nm³. Low moisture content maximises calorific value of the clean gas, an important factor when used as fuel to fire the hot blast stoves and steam generating equipment.

**Minimum water requirement** The annular gap scrubber operates with a low and constant water-to-gas ratio of 0.75 l/m³ of gas. When cooling of the gas is not required, as is the case in installations with top gas energy recovery turbine, the recycle water system capacity can be greatly reduced.

**Low energy consumption** 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.

**Low operating and maintenance cost** The use of high grade materials, the large bore, non-clogging spray nozzles and the simple mechanical design of the scrubber result in extended campaign life with minimum maintenance. Minimum maintenance requirements and low energy consumption equate to reduced operating cost.

**Minimum installation cost** The compact, single tower design conserves space, foundation size, the number and size of access platforms and stairs, the length of gas mains, etc, and therefore the cost of installation. Typically, the weight of vessels, gas mains, structural steel and pipework is 30–35% lower than that of the competing systems.

**Low noise emission** The annular gap scrubber operates with low gas velocities and thus with a low noise level of below 80dB(A) without any special acoustic treatment. This compares with more than 90dB(A) commonly encountered with other designs. MS

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