A Novel Dry-Based System for Safe, Hygienic Energy Recovery from Ferroalloy Furnace Exhaust

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ABSTRACT

Minimizing energy consumption has become a priority for many industrial facilities, both from an economic perspective and in response to political and community pressure to reduce greenhouse gas emissions. Suppressed combustion ferroalloy smelting furnaces typically produce hot and dusty syngas consisting of primarily CO and H_2, which offers the potential for recovery of high-grade chemical energy. However, syngas handling (conveying, cooling and cleaning) can pose a significant risk of explosion or fire, and even minor leaks of this toxic gas can result in poor workplace hygiene and associated acute health risks. Furthermore, many jurisdictions in the world no longer allow for conventional wet gas cleaning due to limited water availability and restrictions on secondary pollution.

Hatch has developed a novel combustible gas treatment process that effectively targets the associated health and safety hazards. The process requires no water and incorporates several patented technologies, including an inherently safe 100% positive pressure gas handling system that enhances in-plant hygiene. This article describes the key technical advantages of this 'dry' process and highlights some of the main drivers for development. Implementation of the system for the largest calcium carbide smelting furnaces in the world at Qinghai Salt Lake Industry Co. (QSLIC) in Golmud, China is profiled as a case study.

1. INTRODUCTION

While ferroalloy smelting has a long established history of continuous development, ranging from the adoption of new technologies to the implementation of countless incremental process improvements, until recently, sustainable development practices have not been at the forefront of this progression. This is rapidly changing as operations target reduced energy costs and regulators in many jurisdictions increasingly call for processes with the lowest environmental impacts.

Exhaust systems for ferroalloy smelting furnaces have evolved greatly in the past century. Originally, gas handling systems for 'open' furnaces consisted of little more than chimneys to disperse contaminants overhead. When environmental regulations eventually called for gas cleaning, many ferroalloy furnaces retained their open design and converted the smelter buildings into large enclosures that were exhausted to a common location for gas treatment. Hygiene within these buildings was notoriously poor, prohibiting access to most areas during normal operation. Eventually, the majority of furnaces migrated to 'semi-closed' or 'closed' designs, with associated suppressed combustion freeboards that allowed for a reduction in the volume of gas to be handled and higher concentrations of CO and H_2. At first, furnace exhaust was cleaned and flared due to the low price of fuel and a lack of incentive to do otherwise. However, safety issues associated with handling the combustible gas and continuing poor hygiene around the furnaces led to the development of full combustion furnace freeboards.

Whereas full-combustion systems effectively addressed many of the safety and hygiene issues associated with suppressed combustion designs, they were generally more costly to install and operate due to the higher post-combustion gas volumes. As a result, despite their inherent disadvantages, suppressed combustion systems continued to be used at the majority of greenfield ferroalloy developments well into the 21st century.

Up to this time, virtually all suppressed-combustions systems utilized wet (i.e., high energy particulate scrubbers) based gas cleaning circuits. Full-combustion systems were generally more flexible, allowing the use of alternative cleaning equipment, including electrostatic precipitators and baghouses, and adopting configurations where the furnace exhaust could be combined with other exhaust sources in the smelter for centralized gas treatment.

About a decade ago, several important trends conspired to influence the prevailing economics:

- Energy costs began to increase rapidly
- Safety became a top priority for many organizations
- Increasingly stricter environmental regulations began to influence equipment selection

Higher energy costs favoured suppressed combustion system configurations, which could be more easily modified to stop flaring and recover the off-gas as chemical energy in a downstream process (such as syngas-fired burners). However, incorporating these modifications made the systems more complex and inherently less safe. Virtually every major ferroalloy facility operating with a suppressed combustion gas handling system has experienced an explosion related incident of some sort, often with associated fatalities.

Stricter environmental requirements were also beginning to surpass the practical capabilities of wet gas cleaning equipment. Many jurisdictions lowered allowable stack particulate matter emissions to 20 mg/Nm^3. EU Integrated Pollution Prevention and Control (IPPC) directives now call for 1-5 mg/Nm^3 [1]. Wet gas particulate cleaning equipment, including venturi-scrubbers and ‘disintegrators’, historically have had significant difficulty in achieving these limits on a consistent basis. Venturi scrubbers must operate with extremely high pressure drop (and associated power consumption) and will often not meet these requirements with typical ferroalloy furnace gases containing high levels of submicron particulate/fume. Furthermore, certain jurisdictions no longer allow wet-scrubbing of combustible gases, due to generation of large volumes of liquid effluent. China, in particular, has numerous ferroalloy furnace gas cleaning facilities with limited or no liquid effluent discharge, and this has become the accepted standard.

Today, emission exceedances and syngas related explosions are still commonplace at many facilities with suppressed combustion exhaust systems, while high CO_2 emissions and higher energy consumption has made full-combustion systems both economically and politically unattractive. These shortcomings provided the motivation for the authors to revisit ferroalloy off-gas handling practices in the hopes of developing a more suitable flow sheet for modern times.

2. CURRENT FERROALLOY GAS HANDLING PRACTICE

Although there are numerous variations, gas handling systems for suppressed combustion exhaust systems can be broadly classified into three categories:

- Wet gas handling processes operating mostly under negative pressure
- Wet gas handling processes operating entirely under positive pressure
- Dry gas handling processes operating mostly under negative pressure

Access to fresh water, ability to discharge liquid effluents, tolerance for explosion / safety risks, capital costs, operating costs and precedence are the key drivers for selection of gas handling technology. Wet gas handling systems are preferred where fresh water is readily available and can be discharged after minimal water treatment. Wet systems under negative pressure are generally found in facilities that have been around for longer as these are the simplest gas handling configurations. Dry gas handling systems appear to be popular in certain jurisdictions (e.g. China), where supply water is not readily available or water treatment is prohibitively expensive due to strict limits for wastewater discharge.

2.1 Wet Gas Handling Processes Operating Mostly Under Negative Pressure

Combustible gas typically exits the furnace and is indirectly cooled through a water cooled duct. Particulate removal is achieved by a wet scrubber. This process often uses venturi scrubbers with induced draft CO gas fans located downstream of the scrubber. Multiple stages of wet quenching, scrubbing and multiple fans in series are often required. A venturi scrubber typically operates with a high pressure drop of 10 kPa or more, resulting in areas upstream of the fan being under significant negative pressure. Therefore, additional monitoring and control is required to minimize the risk of air ingress into the CO/H_2 rich process gas stream which could ultimately lead to explosions.

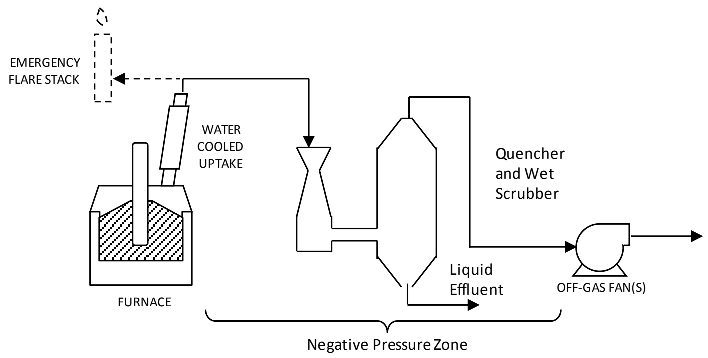

Figure 34: Schematic of wet gas handling process operating mostly under negative pressure

Many facilities that operate at negative pressures employ several methods to mitigate the safety risks, including extensive gas monitoring, frequent maintenance, redundant instrumentation and ‘no access’ area restrictions. For example, Calcium Carbide smelters in North America and Ferrochrome smelters in South Africa still operate this configuration.

2.2 Wet Gas Handling Processes Operating Entirely Under Positive Pressure

In North America and South Africa, several ferroalloy furnaces producing combustible gases employ an alternate wet gas configuration which keeps the majority of the equipment under positive pressure, thereby eliminating the potential for air ingress. For example, Ilmentie smelters, where combustible gas exiting the furnace and water cooled uptake is immediately conditioned in a quench and spray tower. Then the gas is further treated using an eductor and spray tower which imparts sufficient pressure boost through momentum balance to carry the partially cleaned gas under positive pressure to a disintegrator / blower. Alternate configurations include Jet Venturi scrubbers which impart a positive pressure boost through injection of very high pressure water.

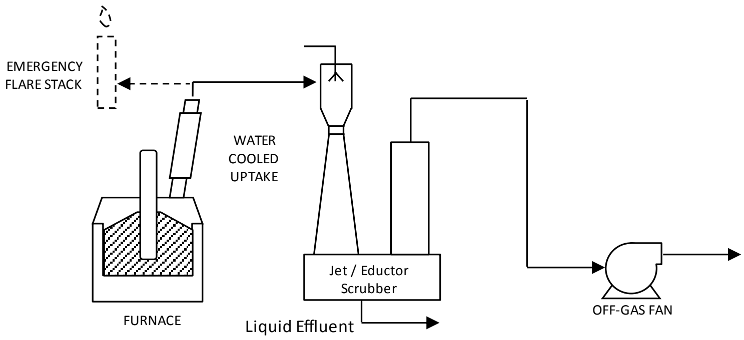

Figure 35: Schematic of wet gas handling process operating entirely under positive pressure

Using this flow sheet, smelters have been operating for over 30 years with excellent safety profiles. The immediate quenching with water results in large reductions in gas volume which can be handled by a compact gas cleaning system. This is advantageous from a capital cost standpoint. It is also easier to keep a compact and low temperature system sealed. The primary drawback is the large volumes of water that must be used to quench and scrub the gas. This problem becomes especially acute in regions where water is a scarce resource. The effluent also absorbs impurities from the gas and must be treated in a wastewater treatment plant prior to discharge. The additional capital and operating cost required to build and operate such a waste water treatment plant is often substantial. Particularly at sites where there are strict limits for wastewater discharge, wastewater treatment plant cost can make a project commercially non-viable. Another drawback of scrubber based systems is that gas cleaning efficiency is generally limited by scrubbing technology.

2.3 Dry Gas Handling Processes Operating Mostly Under Negative Pressure

The majority of new ferroalloy projects with suppressed combustion in China use a dry gas handling system to treat the combustible gas. Alzchem has also been successfully operating a dry gas handling system in Germany. Dry gas handling systems primarily rely on high efficiency baghouses for particulate collection. The Chinese calcium carbide industry has developed baghouse based dry gas handling flow sheets. The majority of these flow sheets is still in the development phase and often requires significant modifications to obtain the necessary performance and on-line time. Typically in these flow sheets the furnace off-gas is indirectly cooled to below 600 ^{o}C in a water cooled uptake.

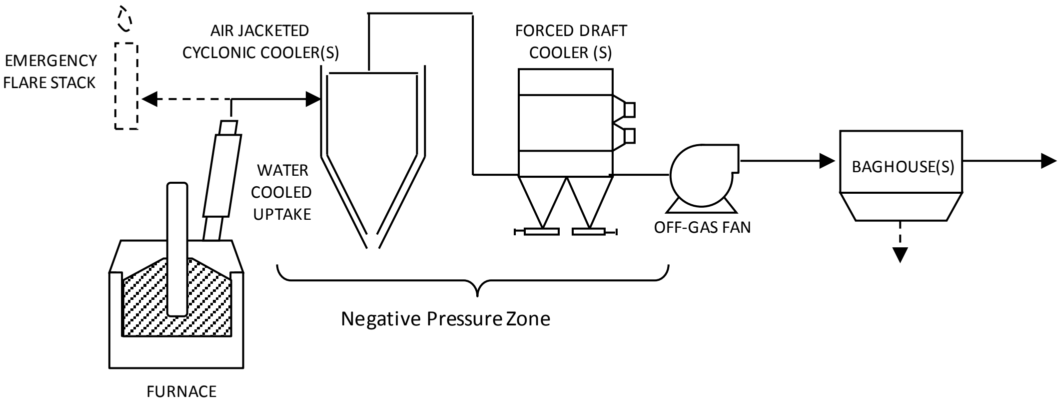

Figure 36: Schematic of Chinese dry gas handling process operating mostly under negative pressure

The gas is then cooled to below 200^{o}C using stages of forced air cooling. This operation commonly takes the form of a forced draft cooler (although Chinese vendors have built alternate coolers which appear to be jacketed cyclones that cool the gas and remove the larger dust particles with unknown performance efficiency). The cooled gas is pressurized and blown through a baghouse for cleaning prior to sending to the end user.

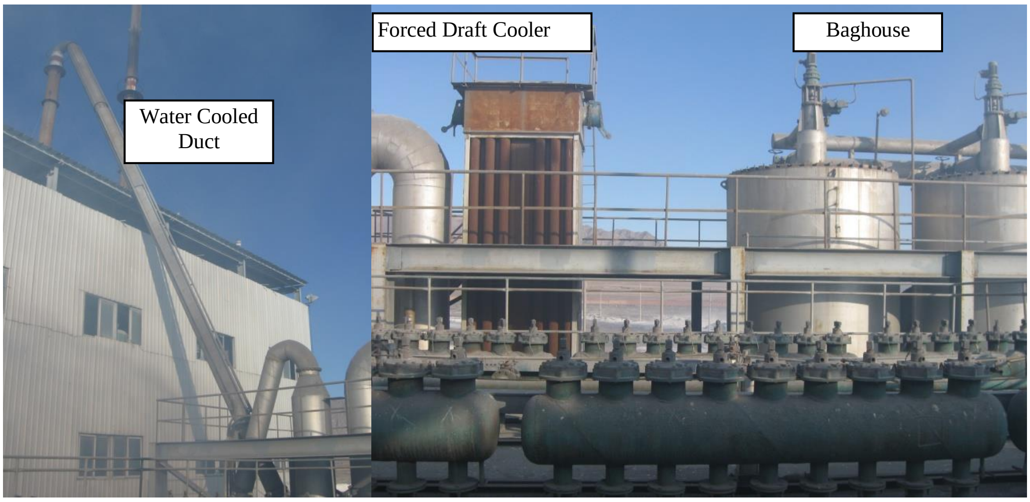

Figure 37: Chinese CaC_2 Smelter Water Cooled Uptake (left); Forced Draft Cooler and Baghouse downstream of Water Cooled Uptake (right)

The primary advantage of a dry system is that it practically eliminates water usage and the need for water treatment. In a wet system, heavy metals and cyanide contained the dust dissolve in the water and treatment of these species in water is often difficult. The filtration efficiency of the baghouses is reliable and 10 mg/Nm^3 can be achieved. At certain facilities, the dry dust collected from the baghouse may be recycled to a cement facility. This dry handling flowsheet also has several drawbacks. The ductwork operates at significantly higher temperatures than a wet system with significant thermal expansion. This demands proper engineering attention to eliminate air infiltration. All equipment upstream of the fan is under negative pressure which frequently causes explosions. This is a challenge that Chinese environmental equipment suppliers have yet to solve. Other considerations include potential hygiene and safety risks associated with dry discharge of CO gas laden dust. These facilities also report reliability issues due to the heavy dust loads at the forced draft coolers, reducing plant throughput. A comparison of the gas handling processes is shown below.

Table 2: Comparison of Gas Handling Systems

Categories		**Dry System**		**Wet System**	
		All Positive Pressure	*Negative Pressure Zones*	*All Positive Pressure*	*Negative Pressure Zones*
Explosion Risks		Low	High	Low	High
Risk of CO gas leakage		High(1)	Low	Medium	Low
Capital Cost	Gas Handling	High	Medium	Low	Low
	Effluent Treatment	None	None	High(2)	High(2)
Operating Cost		Power	Power	Power, Water Treatment Reagents	Power, Water Treatment Reagents
Particulate Emissions		< 10 mg/Nm^3 (3)	< 10 mg/Nm^3 (3)	30 – 50 mg/Nm^3	30 – 50 mg/Nm^3
Dry Dust Reuse		Yes	Yes	No	No

1 – Risk can be mitigated through patented purged flanges
2 – Wastewater includes dust that often contains cyanide and other heavy metals which are difficult to remove
3 – Dependant on dust loading and size distribution but limit can be achieved with a properly maintained baghouse

Based on the above, it was deemed that there would be significant advantages for a gas handling flow sheet that has both the benefits of a dry and positive pressure based system. This led to the development of a new (patented) dry positive pressure based gas handling system.

3. NOVEL DRY POSITIVE PRESSURE SYSTEM

The Hatch dry positive pressure system uses baghouses operating at ~200^{o}C for particulate cleaning. The hot gas exiting the furnace remains slightly positive due to stack effect. The initial cooling prior to entering the furnace off-gas fan is achieved by a water cooled duct followed by recycling cool cleaned gas from downstream of the forced draft cooler. The cooled gas is injected using a custom designed dry eductor to simultaneously pressurize and cool the furnace off-gas. This maintains positive pressure at the inlet of the furnace off-gas fan. The fan discharges the gas through a baghouse and forced draft cooler, keeping the entire gas handling system under positive pressure.

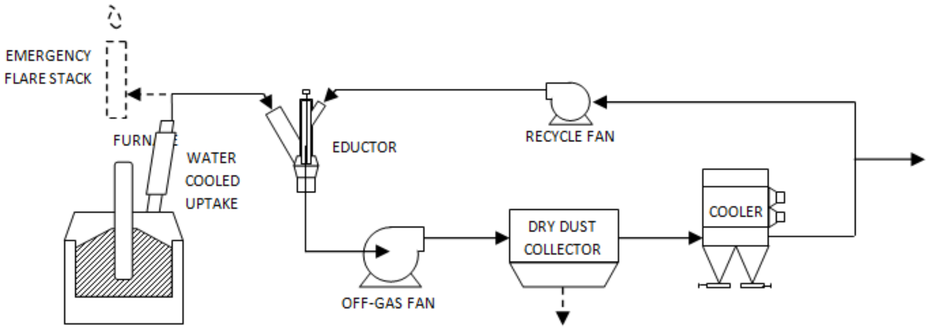

Figure 38: Schematic of Hatch Dry Gas Handling System (One uptake, one train configuration shown)

3.1 Furnace Uptakes and Emergency Flaring System

During normal operation, hot gas is exhausted from the furnace freeboard through a water cooled uptake which provides the first stage of cooling to reduce the gas temperature from 1000ºC to 600ºC. The cooling water flow is monitored for leak detection. Adjustable spring hammers are installed to periodically knock off dust build-up inside the uptake. The water cooled duct discharges to an un-insulated high temperature stainless steel duct, which can also serve as a 'radiation cooler' to obtain additional cooling. The vertical arrangement of the water cooled uptake and the stainless steel duct ensures that the contained gas is always at a positive pressure due to stack effect. A duct to an emergency flare stack branches off from the stainless steel duct. It is used in cases such as furnace start-up, regular and emergency shutdown, when venting is needed to protect the downstream gas handling equipment or when the gas handling capacity is less than required.

3.2 Eductor and Dilution Cooling

Near the end of the stainless steel duct, recycled cool, clean off-gas from downstream of the forced draft cooler is injected into the furnace gas stream via a variable throat dry-venturi (Eductor) to:

- Cool the gas to a temperature suitable for the baghouse
- Generate a positive pressure boost to the furnace gas from the high velocity of the jet

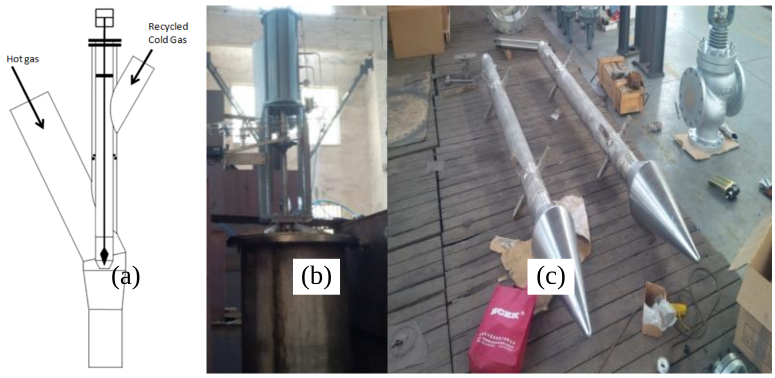

Figure 39: (a) Typical Eductor Configuration, (b) Eductor assembled in shop, (c) Eductor throat

3.3 Gas Cleaning

After dilution cooling, the gas passes through a drop out box before being pressurized by a furnace off-gas fan, which pushes the gas through a baghouse and a forced draft cooler. The gas cleaning area also includes a dust handling system to collect the debris and dust collected from the drop out box and the baghouse. A layout of this gas handling system is shown in Figure 40.

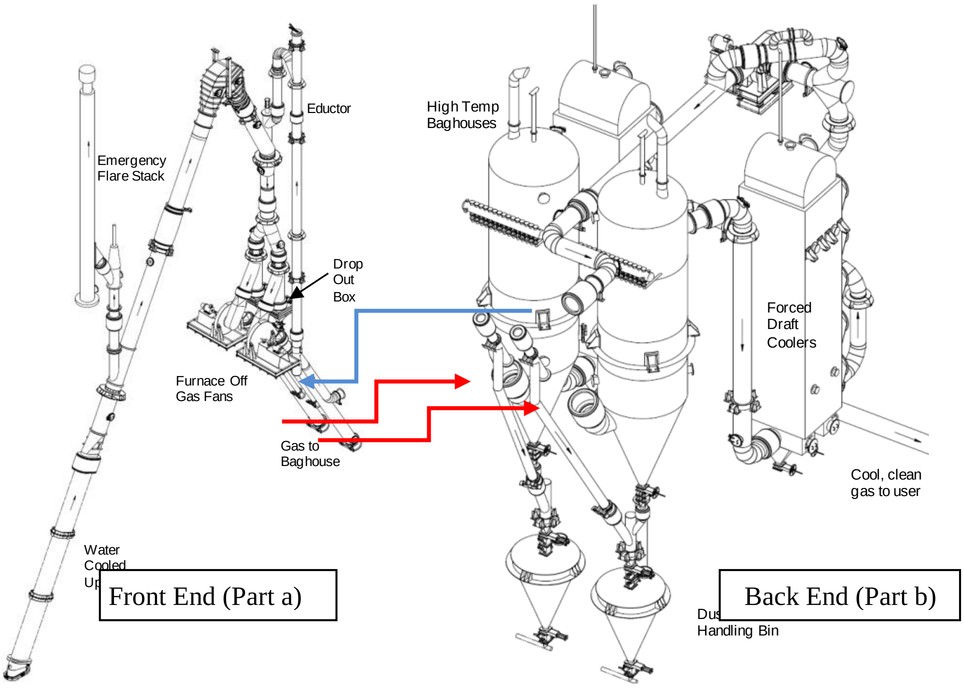

Figure 40: Hatch Dry CO Gas Handling System Front End (Part a), Back End (Part b)

3.4 Novel Features and Best Practices

The design of any combustible gas handling system, in particular syngas, poses several challenges. On one hand, it is generally accepted that maintaining positive pressure is the only inherently safe way to prevent explosion hazards. However, maintaining hygienic conditions is almost equally important due to the toxicity of CO gas. The above flow sheet ensures the gas handling system is inherently safe from risks of explosions. However, to minimize hygiene risks, several novel and best practice features are also included in the design of the dry CO gas handling system.

3.5 Flange Sealing with Leak Detection Monitoring

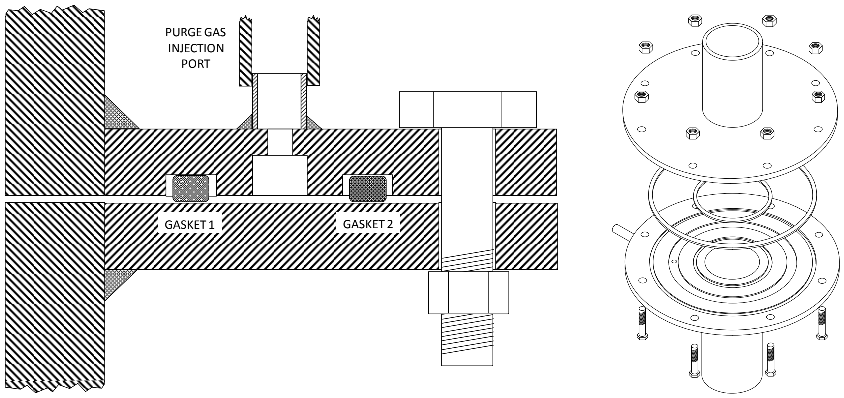

Figure 41: Purge flange section showing gaskets and nozzle (left), assembly view (right)

Leakage of CO gas through flanges was identified as a key hygiene risk when dealing with hot syngas under positive pressure. Syngas typically contains 60 – 80 vol% CO, whereas the Threshold Limit Value (TLV) for CO gas is 25 ppmv. Welding of flanges is a common way to prevent leakages but was deemed too restrictive for maintenance. Therefore, to keep flanges sealed while minimizing leakage, Hatch developed a flange sealing technology that uses pressurized nitrogen to create a positive pressure barrier between two ring gaskets. This prevents CO gas leakage into the atmosphere and allows leak detection through nitrogen flow monitoring, without impacting availability. This flange design is applied in the hot zones of the gas handling system where leakage risk is the highest.

3.6 Dust Recycle Wash System

Entrained CO gas in the dust from the baghouse is another source of hygiene problems. Hatch has designed a dust discharge system that provides a counter current dust wash that cleans hot filtered dust of entrained CO. The dust from the baghouse drops through a near vertical chute and is collected in a purge hopper. A nitrogen injection port is inserted in the chute to provide an upward flow of nitrogen. A second injection port is provided in the purge hopper which keeps a higher pressure in the purge hopper and further minimizes downflow of contaminated gas. The dust flow from one vessel to another is controlled using flap valves. The flap valves are adjusted with designed perforations which allow nitrogen to flow up at all times. The nitrogen flow prevents dust from travelling down when the flap is closed. When the flap opens, the dust falls and is washed by the counter current flow of nitrogen to release the entrained CO gas from the dust.

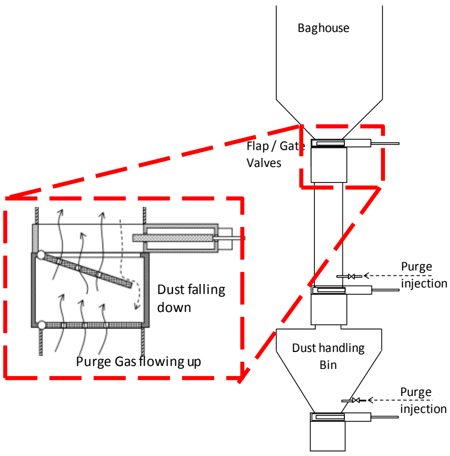

Figure 42: Dust Handling System Schematic

3.7 Other Best Practice Features

The dry positive pressure gas handling system can incorporate various other design features that are considered ‘best practice’ for handling of explosive ferroalloy furnace gas:

- **CO gas leak prevention –** Double bellows (testable) expansion joints provide dual protection and advanced warning in case of leaks in the bellows. Fans and rotating equipment have no split casing and shafts contain purged seals to prevent leakage.
- **CO gas monitoring –** In the event that positive pressure is lost, inline oxygen monitoring of process gas can provide early warning prior to an explosion. An extensive monitoring of ambient CO gas ensures that any gas leaks are detected before personnel exposure above the applicable concentration limits.
- **Water leak detection –** An advanced closed loop leak detection system based on flow and level monitoring minimizes risk of water infiltration into the furnace. Hydrogen can also be detected by a gas analyzer in the uptake to provide advanced warning.
- **Maintenance –** Vertical or sloped equipment surfaces prevent dust from settling. An automated maintenance scheme includes nitrogen and air purging according to European codes [2, 3, 4]. It uses double-block-and-pressurized-dampers, along with water seals to insert blanking plates to allow safe access into the equipment while other portions of the system remain functional.
- **Minimizing explosion risks –** Nitrogen based baghouse pulsing and grounding of all equipment minimizes risk of sparking as an ignition source for explosions.

The inclusion of the above features further mitigate explosion and hygiene risks, improve plant operability and maintainability, and make the system more forgiving over the long term.

4. IMPLEMENTATION OF HATCH DRY GAS HANDLING SYSTEM AT QSLIC

Hatch has supplied four 100 MW calcium carbide furnaces at QSLIC’s smelter complex in Golmud, China, expected to be the largest in the world (and a 5th identical furnace near Xining). All the features of the dry gas handling system described in Section 3 were implemented at QSLIC. As of February 2015, the facility was in the latter stages of construction (Figure 43). As mandated by the client, the system represents the current state-of-the-art and contains the full functionality of a Hatch dry handling system. A facility description and key technical features are described in the sections below.

Figure 43: QSLIC Gas Handling System (under construction)

4.1 Facility Description

Each QSLIC furnace will produce over 11,000 Nm^3/hr of hot, dusty furnace off-gas (60 vol% – 80 vol% CO). Due to the rectangular shape of the furnace and high exhaust gas volume, two off-gas uptakes located at either end of the furnace, were designed to ensure sufficient exhaust capacity. Typical cylindrical baghouses in the Chinese calcium carbide industry do not exceed 3 m in diameter for fabricators to ensure gas tight sealing. Therefore, the QSLIC gas handling system was designed with two gas cleaning trains per uptake (four trains in total) as shown in Figure 44. This allowed the baghouse and forced draft cooler sizes to be maintained within the fabrication capacities of local suppliers.

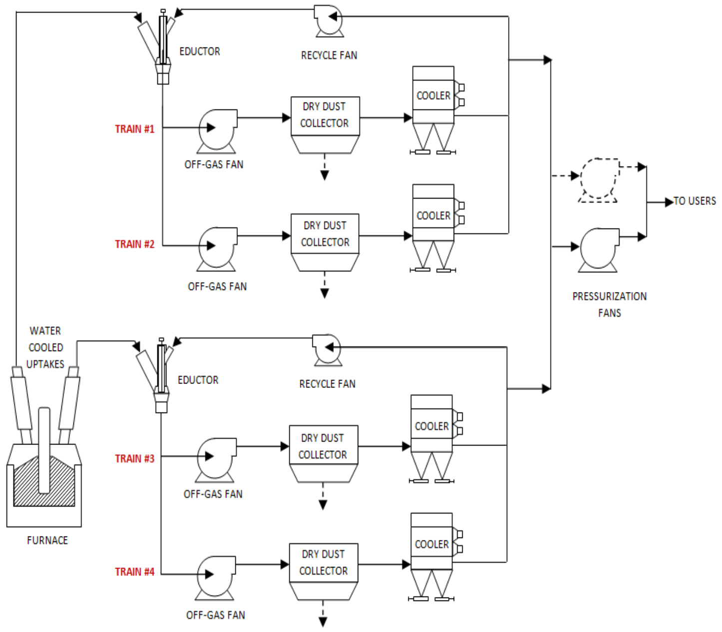

Figure 44: QSLIC Gas Handling System Flow Schematic

To take further advantage of the four train configuration, the equipment in each train was designed with higher capacity such that one train can be isolated for maintenance with no penalty to production. This redundancy was a client requirement and improves overall system availability. The gas from all gas cleaning trains combine and is sent to another fan to convey to a gas holder. From the gas holder, the gas is sent to a set of kilns for use as a supplementary fuel source.

A dust handling system using counter-current nitrogen wash (as described in Section 3.6) was implemented in the QSLIC facility. In order to take advantage of Stack effect and to minimize build up, the QSLIC gas handling system is built vertically with the furnace off-gas fan and baghouses elevated sufficiently. This allowed implementation of a gravity-based dust return system with no mechanical conveying devices, which is expected to significantly reduce maintenance requirements typically associated with dust handling systems. Once the dust handling system is commissioned, the equipment is expected to operate with minimal operator intervention.

4.2 Hygiene Control in Smelter Building

QSLIC's objective to create a state of the art smelting facility also required ways to control fugitive emissions inside the Smelter building. Leakage through furnace electrode seals is typically a major source of emissions inside a smelter building. Therefore, a nitrogen pressurized electrode seal was developed which is expected to result in zero leakage of off-gas into the smelter building. The electrode sealing is continuously monitored to prevent the need for unscheduled maintenance. In addition, a smoke hood is installed to provide sufficient ventilation at the smelter roof elevation such that any nitrogen that escapes into the smelter is immediately exhausted. The smoke hood also provides redundancy against CO exposure in case of a failure of the electrode seals.

4.3 Furnace Pressure Control

To utilize the advancements included in the QSLIC gas handling system design, a sophisticated control system was required. The increased number of trains at QSLIC results in multiple combinations of dampers and variable speed drives that could affect the furnace pressure. If all control sets respond simultaneously to a change in furnace freeboard pressure, the overall response could be coarse. If the controllers respond independently, system control may be unstable.

To eliminate these issues, a single primary controller is used to respond to fluctuations in furnace pressure and the remaining controllers are set to keep the primary controller in its most effective position. This approach can respond to rapidly changing furnace pressures and maximizes the capacity of the supplied equipment. Further logic was added to create an even flow distribution between the gas cleaning trains under maintenance scenarios when one or more trains are offline. The ability to tune and control these loops during commissioning is critical for successful, safe, long term operation of the gas handling system.

4.4 Equipment fabrication and testing

A major challenge for systems handling combustible or toxic gas is ensuring the equipment and ductwork remains gas tight. Therefore, during the fabrication phase, extensive pressure testing of individual duct segments and equipment were recommended. Performing similar pressure testing on-site with a complex duct system is not often practical. Strict fabrication tolerances were also specified, especially for flatness and roughness of flanges, which use hard gaskets that are extremely effective when the corresponding mating flange is designed correctly. The flange sealing mechanism with leak detection features developed by Hatch is a powerful tool for reducing the uncertainty regarding ductwork gas-tight construction. Furthermore, the flanges will be tested during cold commissioning with ambient air to confirm a gas-tight seal exists prior to startup. This is of considerable value at QSLIC due to the presence of less experienced local vendors and an installation / operations team not familiar with installations of this type. It is expected that having these flanges will reduce leaks and hygiene issues in the plant. Similar designs can be adopted for any application that benefits from a tight seal with minimal additional cost.

5. CONCLUSIONS

A 'third-generation' ferroalloy furnace dry gas handling system has been developed by Hatch to achieve compliance with the most stringent global environmental emission limits for air, water and solids. The system combines some of the best dry gas treatment practices established in the Far East with the highest Western standards for reliability and safety. The equipment is fully scalable and can be tailored to suit the specific requirements of most ferroalloy smelting applications. In addition, any syngas handling process which requires particulate removal (e.g. – energy recovery from blast furnace and coke oven gas) could also benefit from incorporating features from this process. Gas conditioning for unique gas fuel users, including gen-sets, is also possible.

The dry gas handling flow sheet is currently being implemented as part of the QSLIC calcium carbide smelting process, which is expected to be commissioned in late 2015. The installation represents the most comprehensive solution offered by Hatch, delivering safer operation with both passive and active monitoring systems. For other ferroalloy applications, the suite of features employed at QSLIC can be tailored based on site-specific regulatory and client requirements. Each feature can be considered an individual module, within which a customized system may be assembled.

6. REFERENCES

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