Design of a primary off-gas scrubber for a ferro-manganese electric arc furnace process

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Design of a primary off-gas scrubbing system for a ferromanganese electric arc furnace process

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ABSTRACT

An electric arc furnace makes use of electrical energy in the form of an arc to heat charged material. In the ferromanganese smelting process the ferric oxide (Fe_2O_3) and manganese oxide (MnO_2) are reduced with coke. The basic reaction that takes place is described in the following equation

$$Fe_2O_3 + 2MnO_2 + 7C = 2FeMn + 7CO$$

The high quantity of carbon monoxide (CO) produced in the process, which has a significantly high calorific value, can be used to generate energy to supplement certain areas of the process. Due to the moisture in the charged material, electrolysis takes place within the furnace, generating hydrogen (H_2) and oxygen (O_2). The high temperature allows a percentage of the carbon monoxide to combust instantly with the available oxygen, which forms carbon dioxide (CO_2). The balance of gas in the process is primarily nitrogen (N_2), which comes from the air drawn into the furnace, as it is impossible to seal the furnace off perfectly. The oxygen from the air also combusts with the carbon monoxide, however there is always a small percentage of oxygen that does not combust. The following table indicates the percentiles of the different gas compositions within the furnace

Gas Composition	Percentage (Typical)	Percentage (Range)
Carbon Monoxide	51.0 %	50.0 - 65.0 %
Carbon Dioxide	13.0 %	10.0 - 20.0 %
Nitrogen	25.0 %	20.0 - 28.0 %
Hydrogen	8.30 %	7.50 - 12.0 %
Oxygen	2.00 %	0.50 - 3.50 %
Methane	0.70 %	0.40 - 0.80 %

Table 1: Typical gas composition percentages

The power input into the furnace process to induce the reduction of the ferric- and manganese oxide, determines the rate at which the reaction takes place. The power input is most commonly measured in MVA and then multiplied by the furnace power factor, which is a function of the electrode characteristics as an inductor, to convert to MW.

The rate at which off-gas is generated does not change significantly with the change in power input, however the dust load in the off-gas stream changes exponentially. Larger particulate is generated with the increase in power, as well as the total mass of dust per cubic meter of gas. The dust loading of the off-gas plays a critical role in the design of an off-gas scrubbing system. The following table indicates the increase in dust load with the increase of power input into the furnace.

Power Input ***[MVA]***	**Dust Emission Rate** ***[µg/s]***
30	1082.877
40	2793.574
50	7206.776
60	18591.82
70	47962.61

Table 2: Dust emission rate as a function of furnace power

Another critical factor of the scrubbing system design is particle size distribution (PSD). The maximum emission of a plant is dictated by environmental legislation, and needs to be adhered to. The greater the dust load in the gas stream, the more efficient the scrubbing system needs to be, because small particulate, which are particles with a sub-micron aerodynamic diameter, is more difficult to remove from a gas stream. The greater the dust load per cubic meter, the greater the quantity of the sub-micron particulate, which significantly influences the design of the scrubber. The required increase in efficiency exponentially increases the power consumption of the scrubbing system, which greatly increases supply costs and service requirements of the plant. The following table indicates the particle size distributions

Particle Size ***[µm]***	**Percentage** ***[Typical]***
< 1.00	20.0 %
1.00 - 5.00	40.0 %
5.00 - 10.0	20.0 %
10.0 - 100.0	15.0 %
50.0 - 100.0	4.00 %
100.0 - 500.0	1.00 %

Table 3: Particle size distribution at 40MW furnace load

These parameters are paramount when conducting the front-end engineering of a scrubbing system for this application. Not only are there financial and commercial implications when failing to adhere to acceptable emissions, but the impact on the surrounding environment can detrimental. Diligent and accurate engineering benefits the customer, supplier and the environment, and satisfies environmental legislative requirements.

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Nomenclature

Sym.	Description	Unit
A	Area	*m^2*
$c_{P,g}$	Specific heat capacity of gas	*kJ/kgK*
$c_{P,l}$	Specific heat capacity of liquid	*kJ/kgK*
C	Cunningham slip correction factor	-
d	Inside diameter	*m*
D	Outside diameter	*m*
d_l	Liquid droplet diameter	*m*
d_{lc}	Liquid droplet cut-off diameter	*m*
d_p	Particle diameter	*m*
η	Efficiency	-
h	Enthalpy	*kJ/kg*
H	Height	*m*
k	Thermal conductivity	*W/mK*
K	Geometrical constant	-
l	Length	*m*
m	Mass	*kg*
M	Moment	*N.m*
m_l	Liquid mass	*kg*
m_g	Gas mass	*kg*
μ	Viscosity	*Pa.s*
μ_l	Liquid viscosity	*Pa.s*
μ_g	Gas viscosity	*Pa.s*
N	Number of	-
p	Pressure	*kPa*
P	Power	*kW*
p_{atm}	Atmospheric pressure	*kPa*
p_g	Gas pressure	*kPa*
ψ	Inertial impact parameter	-
Q_g	Gas flow rate	*m^3/s*
Q_l	Liquid flow rate	*m^3/s*

$\boldsymbol{\rho}$	Density	kg/ m^3
$\boldsymbol{\rho_g}$	Gas density	kg/ m^3
$\boldsymbol{\rho_l}$	Liquid density	kg/ m^3
$\mathbf{v}$	Velocity	m/s
$\mathbf{V}$	Volume	m^3
$\mathbf{v_g}$	Gas velocity	m/s
$\mathbf{v_H}$	Velocity head	m/s
$\mathbf{v_{th}}$	Throat velocity	m/s
$\mathbf{V_g}$	Gas volume	m^3
$\mathbf{V_l}$	Liquid volume	m^3
$\mathbf{t}$	Time	*s*
$\mathbf{T}$	Temperature	℃
$\mathbf{T_g}$	Gas temperature	℃
$\mathbf{T_l}$	Liquid temperature	℃

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1 Introduction

This dissertation has been written to approach a problem in the industry from a practical point of view. Projects in the industry are seldom executed will all the components of the plant in parallel, as tests need to be done to determine a sound solution. A furnace is a very sensitive process in that two identical furnaces can deliver different results, both of which might need to be catered for differently.

The approach of this dissertation is for the reader to be able to execute the design of a primary off-gas scrubber in the same order as would be done by a specialist engineering company. This allows the reader to apply the knowledge directly to a similar application, which is the basis of a sound engineering report.

The information starts off with a basic understanding of the environment; more specifically the atmosphere, and then develops into the complex design phase of the plant.

1.1 The Atmosphere

All organisms, ranging from the largest species to the smallest micro-biological cells, form part of our environment; humans being the only organism that can physically alter its conditions. These physical changes can be detrimental if not managed correctly, resulting in imbalance in the environment. Our survival is dependent on the longevity of this balance, as the repercussions of even the tiniest physical change can set events in motion that constitute a large scale effect.

Industrial expansion increases annually at an exponential rate as a result of the rapid growth in the population globally. Agriculture and deforestation contributes greatly towards increased pressure on the environment, as the physical changes occur faster than it can recover.

Apart from the physical changes to the environment, we also need to consider the rate at which natural resources are polluted. Clean air and water are fundamental resources for the survival of living organisms, of which there is a finite supply within our atmosphere.

Earth's atmosphere is host to the air we breathe, barring its escape into space. It is occupied by four primary layers, namely the troposphere, stratosphere, mesosphere and thermosphere, in ascending order as seen in Figure 1-1. There are significant changes in the properties of air between these layers, due to changes in temperature and pressure. These changes can be simply explained by the ideal gas law in equation 1-1 (Clapeyron, 1834).

$$pV = nRT \tag{1-1}$$

1.1.1 Thermosphere

The thermosphere is the highest layer in the atmosphere before reaching the exosphere, extending from an altitude of approximately 80 km, however there is a significant continual variation in altitude due to solar activity (Duxbury & Sverdrup, 2002). The temperature in this layer can exceed 1,200 °C, however this would not be able to be transferred as sensible heat due to thermal radiation losses.

Water molecules are far too large and heavy to exist at this altitude, rendering the thermosphere free of water vapour. Even air is scarce; so much so, that a single molecule can travel an average of one kilometre before colliding with another (Donald, 2005). The International Space Station orbits within the thermosphere at a mean altitude of 330 km, and a maximum altitude of 420 km (Peat, 2013).

1.1.2 Mesosphere

The mesosphere is the second highest layer of the atmosphere and occupies the volume between an altitude of approximately 50 and 80 kilometres. Temperatures here decrease significantly as the mesopause is approached, averaging -85 °C and reaching -186 °C, earning it's title as the coldest place on earth (McNaught & Wilkinson, 1997).

Conventional aircraft cannot operate at this altitude due to insufficient oxygen, and the atmospheric drag and gravitation force is too great for orbital spacecraft; it can only be accessed by sounding rockets and weather balloons. As a result, this layer in the atmosphere is poorly understood.

1.1.3 Stratosphere

The stratosphere is the third highest layer in the atmosphere, ranging between an altitude of approximately 12 and 50 kilometres, and host to the ozone layer. The temperatures in the upper, tropopause, and lower, stratopause, layers of the stratosphere range between -60 °C and 0 °C respectively; inversely proportional to the decrease in altitude (James ,1993). This is due to the ability of the ozone layer to absorb UV radiation from the sun.

Atmospheric conditions in the stratosphere are very stable, due to the temperature profile. This allows specialised aircraft to access this altitude, and maintain optimized fuel burning efficiencies and low drag-force losses.

1.1.4 Troposphere

The troposphere extends from the earth's surface towards the tropopause, thus being the lowest layer of the atmosphere. Temperatures range between -60 °C and 15 °C and the atmospheric pressure is sufficient to sustain the majority of life-forms and activity. It is composed of a variety of gasses, primarily nitrogen and oxygen; other trace gasses are present in small concentrations.

The troposphere is the atmospheric layer in which the industry operates, thus it will be the primary focus of this study.

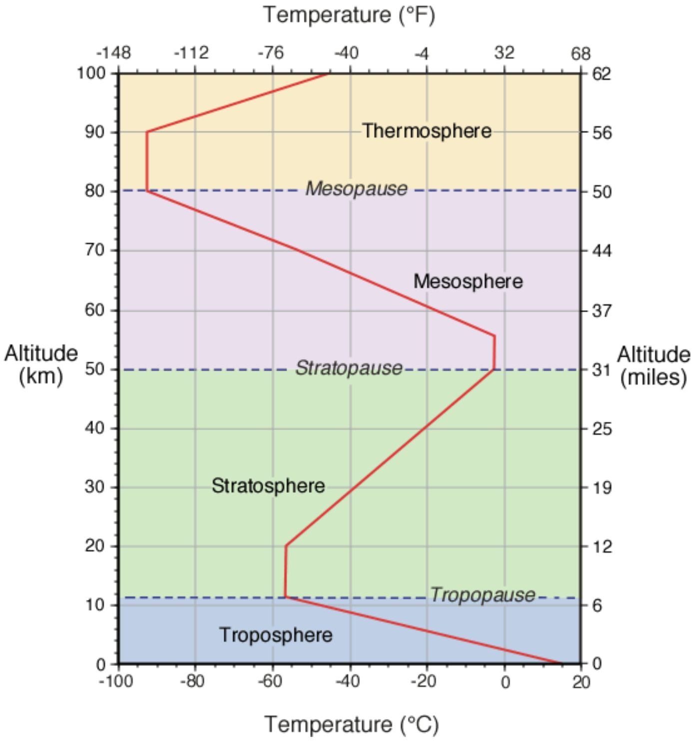


Figure 1-1: Vertical change in the global atmospheric temperature (Pidwirny, 2006)

1.2 Clean Air

Clean air, or unpolluted air, is the concept where no man-made pollution contributes towards its composition. This concept can only be estimated, as humans where polluting the atmosphere long before the technology was available to measure the air composition. There is no geographical location now on earth that can now be declared a clean air region, as there are no references to support it.

The atmosphere is not only composed of a variety of dry permanent gases. Air contains water vapour, organic vapour and suspended particulate matter. Vapour acts as gas in air when it is above its condensation temperature, however the behaviour changes to that of a liquid when the air is saturated. Table 1-1 indicates the volumetric composition of conceptual clean air, both dry and wet.

Table 1-1: Gaseous composition of both dry and wet basis conceptual clean air (Vallero, 2006)

Gas	Gaseous Composition (Dry Basis)		Gaseous Composition (Wet Basis)	
	ppm (vol)	*μg/m^3*	*ppm (vol)*	*μg/m^3*
Nitrogen	780,000	8.95 x10^{8}	756,500	8.67 x10^{8}
Oxygen	209,400	2.74 x10^{8}	202,900	2.65 x10^{8}
Water	-	-	31,200	2.30 x10^{7}
Argon	9,300	1.52 x10^{7}	9,000	1.47 x10^{7}
Carbon Dioxide	315	5.67 x10^{5}	305	5.49 x10^{5}
Neon	18	1.49 x10^{4}	17.4	1.44 x10^{4}
Helium	5.2	8.50 x10^{2}	5.0	8.25 x10^{2}
Methane	1.2	7.87 x10^{2}	1.13	7.63 x10^{2}
Krypton	1.0	3.43 x10^{3}	0.97	3.32 x10^{3}
Nitrous Oxide	0.5	9.00 x10^{2}	0.49	8.73 x10^{2}
Hydrogen	0.5	4.13 x10^{1}	0.49	4.00 x10^{1}
Xenon	0.08	4.29 x10^{2}	0.08	4.17 x10^{2}

The values in the table 1-1 are expressed as metric units, which is micro grams per cubic meter of air. A simple calculation is used to convert the values in ppm (parts per million) to µg/m^3, indicated in equation 1-2. For this calculation, a standard temperature and pressure are assumed as 25°C and 101.325 kPa respectively.

$$\begin{aligned} 1\text{ ppm} &= \frac{1\text{ liter pollutant}}{10^6\text{ liter air}} \\ &= \frac{(1\text{ liter}/22.4) \times \text{MM} \times 10^6 \mu g/gm}{10^6\text{ liters} \times 298K/273K \times 10^{-3} m^3/liter} \\ &= 40.9 \times \text{MM}\ \mu g/m^3 \end{aligned} \quad (1\text{-}2)$$

1.3 Particulate Matter

Particulate is the collective term for small solid particles and droplets of liquid; it originates from both man-made and natural sources. The produced particulate is indicated in table 1-2, and it is interesting to note that natural sources generate a larger sum total of particulate than man-made sources; however the man-made particulate pollution quantity is far from negligible (Weiner & Matthews, 2003).

The values in table 1-1 does not incorporate the particulate matter that is always present in air, varying in weighted presence depending on various factors. Each gas and vapour exists as an individual molecule, and its movement is random. Particles form as a result of molecules that join together; both similar and dissimilar. The behaviour of these particles depends on the conditions of the atmosphere, as they can serve as a surface for vapours to condense to, or a chemical reaction can take place between the molecules and the atmosphere.

It is common for particles to adhere to each other when they collide in the atmosphere, due to the attractive forces on their surfaces. The agglomeration of the particles becomes progressively larger, and thus increases in mass. The particles eventually falls from the air, as its mass is too great to remain airborne; the process is known as sedimentation (Boubel, *et. al.*, 1994). The presence of a particle in the air is dependent on its weight versus its aerodynamic diameter and displacement of atmospheric volume. The mass of a particle can be expressed using equation 1-3, where the mass (m_p), density (ρ) and radius (r) are in metric units.

$$m_p = \frac{3}{4}\pi\rho r^3 \quad (1\text{-}3)$$

Particulate matter originates from both natural and man-made sources. The annual discharge of particulate matter from natural and man-made sources is 800 - 2,000 and 200 - 500 million tons respectively (A Kumar De, A Kumar De, 2005).

Table 1-2: Annual world-wide discharge of particulate matter into the atmosphere (Kumar de and Kumar de, 2005)

Particulate Matter	**Annual Discharge**	
	Natural Sources	Man-Made Sources
	Million Tons	*Million Tons*
Total Particles	800 - 2,000	200 - 450
Dust and Smoke	-	10 - 90
Salt and Forest Fires	450 - 1,100	-
Sulphate	130 - 200	130 - 200
Nitrate	330 - 35	140 - 700
Hydrocarbons	15 - 20	75 - 200

Particulate varies in size from 0.0002µm to 500µm, depending on their composition and density. Clean air can contain as little as a few hundred particles per cm³, however highly polluted urban and industrial air can exceed 100,000 per cm³.

There is a greater presence of particulate matter in the troposphere due to the increased density and gravity at lower elevations. The volume of atmosphere lower than 100m is highly polluted above urban and industrial areas. The pollutants in the atmosphere undergo a chemical reaction in the presence of water vapour, oxygen and UV radiation. These reactions produce secondary pollutants, as indicated below, which are harmful to vegetation, animals, material and humans.

$CO_2 + H_2O \rightleftharpoons H_2CO_3$ Carbon dioxide → Carbonic acid

$SO_2 + H_2O \rightleftharpoons H_2SO_3$ Sulphur dioxide → Sulphurous acid

$NO_X + H_2O \rightleftharpoons HNO_3$ Nitrogen oxides → Nitric acid

Meteorology is based on the physical properties of the atmosphere, such as temperature, pressure, density, moisture and pollutants. Chemical reactions that take place in the atmosphere also have an effect on these physical properties.

The dispersion of pollutants in the atmosphere is dependent on the movement of the air, which is set in motion by temperature differences. This cycle dilutes the higher concentrations of pollution in area, but transfers them to a different location as a result. Mankind is partly responsible for changes in the earth's meteorology, by conducting activities as indicated in table 1-3.

Table 1-3: Major emission sources of pollutants (Spengler and Sexton, 1983)

Pollutant	Major Emission Source
Allergens	Animals, insects
Asbestos	Fire retardant materials, insulation
Carbon dioxide	Metabolic and combustion activities
Carbon monoxide	Fuel burning, reduction and smelting processes
Formaldehyde	Particleboard, insulation, furnishings
Micro-organisms	Humans, fauna, flora, air-conditioners
Nitrogen dioxide	Fuel burning
Organic substances	Adhesives, solvents, building materials, volatilisation, paints
Ozone	Photochemical reactions
Particles	Re-suspension, combustion
Polycyclic aromatic hydrocarbons	Fuel combustion
Pollens	Outdoor air, fauna
Radon	Soil, building materials
Fungal spores	Soil, fauna, internal surfaces
Sulphur dioxide	Fuel combustion, calcining processes

1.4 Air Quality Standards

Each pollutant has a TLV (Threshold Limit Value) which can be hazardous to our health if exceeded. Typical pollutants in the industry are indicated in table 1-4 with each of their TLVs. Typically, a person can be exposed to a pollutant, provided it is below the TLV, for no more than 40 hours per week without having adverse health effects.

Table 1-4: Threshold Limit Values (TLV) for a variety of common gases and vapours in the industry (Kumar De and Kumar de, 2005)

Pollutant	Threshold Limit Values	
	ppm	*mg/m^3*
Acetone	750	1780
Ammonia	25	18
Arsenic	0.2 - 0.5	-
Benzene	10	20
Cadmium	-	0.05
Carbon dioxide	5000	9000
Carbon monoxide	50	50
Carbon tetrachloride	5	30
Chlorine	10	30
Chloroform	10	50
Hydrogen chloride	5	7
Hydrogen sulphide	10	14
Lead	-	0.2
Nitric oxide	25	30
Ozone	0.1	0.2
Sulphur dioxide	2	5

2 Environmental Awareness

Environmental awareness is on the increase all around the world, and environmental sustainability has become a massive movement to preserve our planet earth, with which we have been blessed. Activities have been derived to reduce the negative influence that mankind has on the environment, and many of these activities have become a global standard by which to conform. These activities range from pollution treatment plants, to the intervening of certain production processes which result in pollution, to the redesigning of products and services to lower their environmental impact (Vezzoli & Manzini, 2007).

To better understand the root causes of our environmental problems, a closer look needs to be taken at mankind; more specifically Western civilization. Western civilizations are often described as destructive, exploiting, and a general uncaring attitude towards the environment. Many arguments exist regarding the origin of our destructive tendencies towards the environment, which include religion, social structure, economic structure, and how we accept technology (Peirce *et al*., 1998).

No matter what the origin of our tendencies is, it is important to maintain an ethical attitude towards the environment. The environment must be treated as an entity, because it is something that mankind shares. By polluting an area through a production process or service, the direct environment is affected which, in turn, affects the population, fauna and flora residing in that area. Ralph Waldo Emerson expressed his thoughts on the instrumental value of nature to mankind as material wealth, the potential to recreate, and aesthetic beauty. Environmental ethics can be considered as a conservational ethic, because it involves conserving resources to benefit us in the long-term (Saravanan, *et al*., 2005).

2.1 Global Emissions

Figure 2-1 indicates the annual carbon emission contribution by region since the 1800's. It is clear that there is an exponential increase, which is influenced by the increase in technological processes, and the growth in population.

Even though the industry (processes, mining and transportation) contributes the largest part towards man-made pollution and emission, it is important to understand that each and every one of us has a moral accountability and responsibility to preserve our environment. This is not only beneficial to man-kind, but generations to follow.

Every positive contribution that a person makes, however small, ultimately makes a large positive contribution towards environmental preservation on the whole. We must maintain the attitude that, even though we are tiny in relation to a factory or mine, we are instrumental in setting a standard of environmental conservation, and that this attitude needs to start small in our personal actions; it will then filter through to the larger industries.

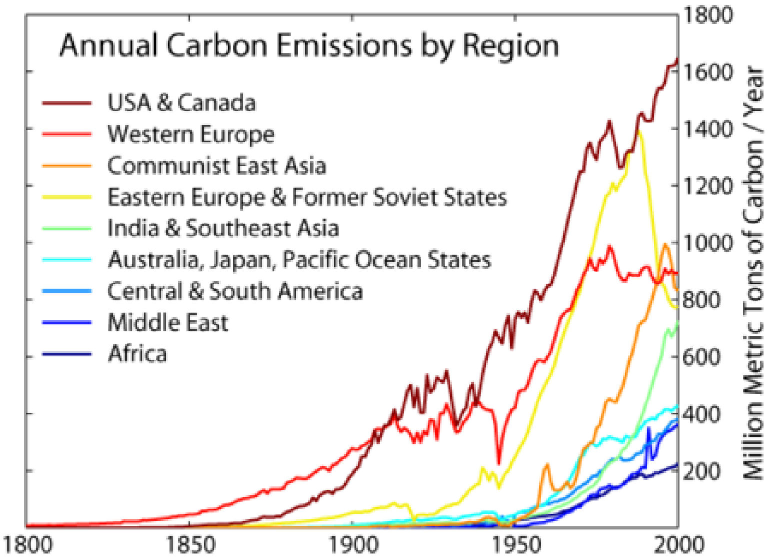


Figure 2-1: Linear scale of annual carbon emissions by region (Marland *et al*., 2007)

2.2 Environmental Legislation in South Africa

Regulations of environmental protection in South Africa can be traced back to the 1940's, which indicates early awareness in terms of environmental conservation (Van der Linde & Feris, 2010). Legislation, however, was only introduced much later as The Environmental Conservation Act, Act 73 of 1989. In September 1997 the Environmental Impact Assessment Regulations were promulgated. This contributed towards a proactive approach to mitigate and manage negative environmental impacts.

Section 24 (The Environmental Law) was included into the South African Constitution, Act 108 of 1996, which entitles every person to an environment which is not detrimental to their health and well-being.

To make this constitutional mandate even more effective, the environmental law in South Africa has been under intense revision since 1996. The National Environmental Management Act 107 of 1998 was promulgated to support and increase the effectiveness of this constitutional mandate (Van der Linde & Feris, 2010). The National Environmental Management Act is a progressive development which sets environmental standards to guide government, institutions and individuals in making environmental decisions. The National Environmental Management Act also provides the following elements:

- Environmental principles
- Co-operative governance
- Duty of care
- Enforcement mechanisms
- Integrated environmental management

Additional environmental management acts have been promulgated, such as The National Environmental Management: Waste Act of 2008, which strengthens The National Environmental Management Act.

2.3 Offences and Penalties

For the legislation to be effective, government has the right to enforce penalties on any entity that does not abide by the rules and regulations set out by the relevant act.

2.3.1 Offences

Section 51 of the National Environmental Management: Air Quality Act 39 of 2004 stipulates the possible offences regarding air quality. The following are important:

- Provision needs to be made in terms of the following:
    - Section 22: Licences and listing
    - Section 25: Consequences of involvement of an appliance or action declared as a controlled emitter
    - Section 35(2): Responsibility for controlling and preventing offensive odour emissions
- Pollution prevention plans need to be drafted and submitted, according to Section 29(1)b and Section 29(2)
- An atmospheric impact report needs to be submitted, according to Section 30
- The Minister needs to be notified, according to Section 33
- The standards for a controlled emitter, according to Section 24

2.3.2 Penalties

Section 52 of the National Environmental Management: Air Quality Act 39 of 2004 stipulates the penalties which can be evoked on individual or institution if convicted of an offence referred to Section 51 above.

1) The following penalties can be evoked:
    a) A maximum fine of R10 million and/or 10 years imprisonment for an initial offence
    b) A maximum fine of R5 million and/or 5 years imprisonment as a second or subsequent offence to the initial offence
2) When the fines are imposed, the following needs to be considered:
    a) The severity of the offence in terms of safety, well-being, health and the environment
    b) The benefits (whether monetary or other) that where accrued through the offence
    c) The contribution towards the total pollution in that area

2.4 Industrial Pollution

More than 90 per cent of air pollution around the world is comprised of five primary pollutant contributors (Kumar De & Kumar De, 2001), and the primary contributor of the total pollutants globally is transportation (46 per cent). The five pollutants are:

1) Particulates
2) Carbon dioxide (CO_2)
3) Nitrogen oxides (NO_X)
4) Hydrocarbons (HC)
5) Sulphur oxides (SO_X)

Carbon monoxide is the largest pollutant in the industry, which has a total global emission mass of more than all the other pollutants combined. Particulate pollutants, however, are much more poisonous and dangerous than any of the other pollutants (Kumar De & Kumar De, 2001).

Table 2-1 indicates the air quality standards as defined in Schedule 2 of Section 63 of the National Environmental Management: Air Quality Act 39 of 2004.

Table 2-1: Air quality standards according to Schedule 2 of Section 63 of the National Environmental Management: Air Quality Act 39 of 2004

Composition	**Maximum Instant Peak @ 25°C and Atmospheric Pressure**		**Maximum Average Over 10 Minutes**		**Maximum Average Over 1 Hour**		**Maximum Average Over 24 Hours at a Maximum of 3 Times per Year**	
	Value	*Unit*	*Value*	*Unit*	*Value*	*Unit*	*Value*	*Unit*
Ozone (O_3)	0.25	*ppm*	-		0.12	*ppm*	-	
Nitrogen Oxides (NO_X)	1.4	*ppm*	-		0.8	*ppm*	0.4	*ppm*
Nitrogen Dioxide (NO_2)	0.5	*ppm*	-		0.2	*ppm*	0.1	*ppm*
Sulphur Dioxide (SO_2)	500	$\mu g/m^3$	0.191	*ppm*	0.048	*ppm*	-	
Lead (Pb)	2.5	$\mu g/m^3$ *monthly average*	-		-		-	
Particulate Matter <10µm (PM10)	60	$\mu g/m^3$ *annual average*	-		-		180	$\mu g/m^3$
Total Suspended Solids	100	$\mu g/m^3$ *annual average*	-		-		300	$\mu g/m^3$

3 Pollution Control

Air pollution control can generally be described as the technology of “separation” (Schifftner, 2002). This means that pollutants are separated from the carrier gas. By separating the pollutants from the carrier gas, the pollutants can then be easily collected and then disposed of, or recycled.

The problem with gaseous pollutants, especially aerosols which are fine solid or liquid particles usually smaller than 0.5µ, is that we inhale them. Once inhaled, our respiratory systems are susceptible to absorbing these gases. The toxicity is not always the problem; it’s that the pollutant attaches itself to the bronchial area and alveoli sacs. The lungs then become lined with these pollutants, and the absorption of oxygen is restricted; thus suffocation becomes the threat and not necessarily the toxicity.

There are many solutions to pollution control in the industry, each of which has its own advantages and disadvantages. There are many criteria to consider when selecting the appropriate pollution control system.

3.1 Wet Collection

Wet collectors make use of the viscosity of a liquid, usually water, to separate the pollutant from the carrier gas. Studies conducted around the rate of particles settling and motion kinetics, have indicated that particles larger than 5µm behave inertially, while particles smaller than 2µm behave like gases (Schifftner, 2002).

Wet collectors or scrubbers make use of the following three principles for separation to occur, illustrated in Figure 3-1:

- **Impaction**
  Impaction is the most recognisable method of particulate removal (Schifftner & Hesketh, 1986). This occurs when the pollutant accelerates and is impacted into a droplet of liquid or a surface. The kinetic energy and inertia is sufficient for the particle to follow a predetermined path, and then penetrate the surface tension of the scrubbing liquid droplet. Once the particle has penetrated and is inside the droplet, the combined aerodynamic diameter of the droplet and particle is larger, which makes it easier to separate from the carrier gas.
- **Interception**
  Interception occurs in the particles which are not collected by impaction. Rather, they travel close enough to the surface of the liquid droplet to be attracted; however the particle penetrates the droplet at an angle far less than 90° (Schifftner & Hesketh, 1986). The particle does not have sufficient inertia to travel in a predicted path, yet it has enough kinetic energy to penetrate the surface tension of the droplet.
- **Diffusion**
  Diffusion occurs mostly in particles smaller than 0.5µm. As discussed earlier, a particle smaller than 2µm tends to behave like a gas; which incorporates electrostatic forces, turbulence factors and gas density irregularities (Schifftner & Hesketh, 1986). The particle bounces between the droplet and the gas stream which forms around the droplet. Once the particle has attached itself to the surface of the droplet, there is insufficient energy for the particle to penetrate the surface tension of the droplet. In impact plate is then used to force the particulate to be engulfed by the droplet.

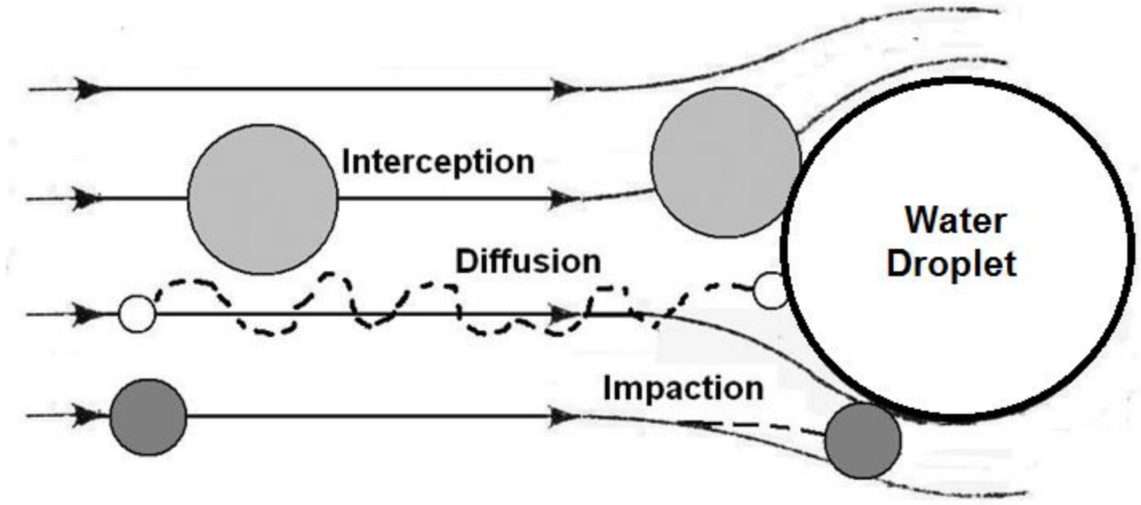


Figure 3-1: Three methods of particulate removal with a wet system (Schifftner, 2002)

3.1.1 Venturi Scrubbers

Venturi scrubbers are a type of wet scrubber that makes use of a sudden change in the carrier gas velocity to atomise streams of liquid into tiny droplets; depending on the application, the scrubbing liquid is usually water (Schifftner, 2002). This sudden change in the carrier gas velocity is implemented by creating a pressure drop across the venturi throat, which results in the acceleration of the gas (Theodore, 2008). Particulate matter and soluble gasses are then transferred into the water droplets.

Venturi scrubbers are able to remove particulate with an aerodynamic diameter as small as 0.6 µm. Studies have also been conducted where sub-micron particles have been removed when a pressure drop of about 15kPa was induced in the venturi (Schifftner, 2002). Venturi scrubbers are also capable of handling large volumetric flow rates of carrier gas, whilst still maintaining the desired efficiency.

3.1.2 Packed Towers

Packed towers work similarly in principal to a venturi scrubber, however it consumes less energy to atomise a liquid. A packed tower is a hollow column that contains a fill, such as pall-rings, which increases the surface area of the tower. Liquid then enters the top of the column, and the gas stream enters at the bottom. The column is always wider than the inlet duct, which allows the upward velocity of the gas stream to decrease. The upward velocity of the gas stream is determined as a function of the contact time required between the liquid and the gas.

Packed towers are commonly used for the treatment of noxious gas streams, and the neutralization of acidic gas streams. The dosing agent is added to the recirculation liquid, thus being dispersed across the whole area of the tower.

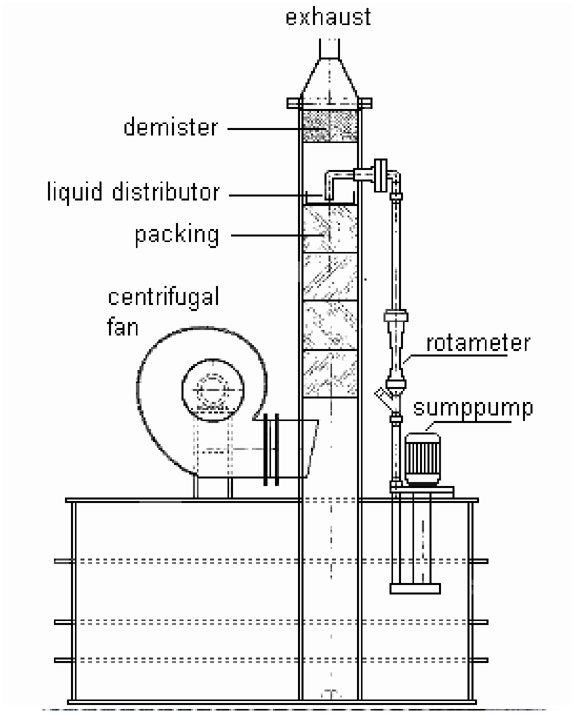


Figure 3-2: Packed tower scrubber (Schnelle & Brown, 2000)

3.1.3 Fluidized Bed Scrubbers

Fluidized bed scrubbers make use of a two-phase mixture of gas and liquid, similar to the operating principal of a fluidized bed boiler. The mixture is a constantly agitated bed, into which the gas is injected. The agitation is designed to increase the mass transfer rate, as the dissolution of a gas into liquid is improved by stirring (Schifftner, 2002).

These scrubbers are primarily used in gaseous applications where the particulate present can cause blockages in other designs, such as packed towers. The particulate is generally in the carrier gas stream, however it can be a by-product of the absorption reaction. Typical applications include

- Chlorine (Cl_2) and chlorine dioxide (ClO_2) control
- Sulphur dioxide (SO_2) control using caustic (NaOH) as a neutraliser
- Sulphur dioxide (SO_2) control using a limestone slurry
- Odour control like hydrogen sulphide (H_2S)
- Gas quenching and condensing
- Pre-scrubbing of gases upstream of high efficiency elimination devices

3.2 Dry Collection

For large particulate matter which exceeds an aerodynamic diameter of about 50µm, the most common collectors are knock-out chambers and traps (Schifftner, 2002). The principle is to slow down the particle as far as possible so that the particle will drop out.

3.2.1 Filtration Collector

Collection devices that make use of fabric bags to filter out particulate matter are usually referred to as “baghouses” (Schnelle & Brown, 2000). These bags are mounted on a tube sheet, which is arranged closely together and enclosed in a large housing. These types of filters are typically used when the particulate matter size ranges between 50µm and 75µm.

Baghouses separate the contaminant from the carrier gas by passing the gas through a filtration media (Schnelle & Brown, 2000). The filtration media is usually made of one of the following:

- Fabric (such as industrial cloth)
- Porous material (such as ceramic candles or tubes)
- Paper (such as the bags inside household vacuum cleaners)

Each of these different filtration media types are used for a specific application, typically depending on the following aspects of the application:

- Contaminant type and composition
- Contaminant size (aerodynamic diameter)
- Volumetric flow rate of the carrier gas
- Inlet temperature of the carrier gas
- Inlet pressure of the carrier gas

The inlet temperature of the carrier gas is very important to consider, because the filtration media can be damaged if the temperature is too high; usually exceeding 260 °C (Schnelle & Brown, 2000). When applications exceed these temperatures, evaporative coolers are used to reduce the carrier gas temperature. This, however, warrants larger construction, cost, ground area, operating power consumption, and maintenance implications.

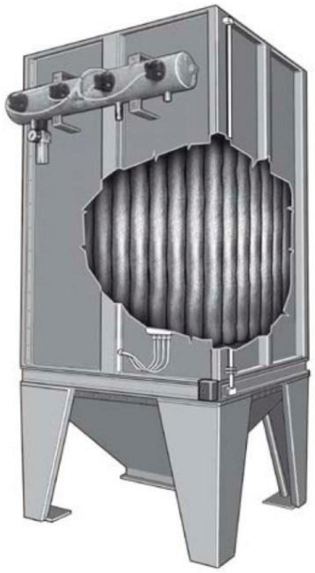


Figure 3-3 : Typical fabric filter (Schnelle & Brown, 2000)

3.2.2 Dry Cyclone Collector

Another form of a dry collector is a dry cyclone collector, which makes use of the angular velocity and centrifugal force of the particulate to force them outward onto the inner surface of the cyclone shell. The particulate then slides down the sides of the cyclone and is deposited through a hopper into a collection container. The basic principal of a typical dry cyclone collector is indicated in Figure 3-2.

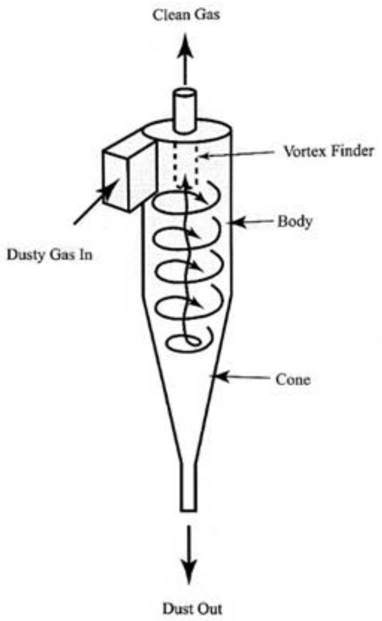


Figure 3-4 : Standard cyclone (Schnelle & Brown, 2000)

Schifftner (2002) states that a cyclonic collector's means of particulate removal is based on Newton's second law ($F = m{\cdot}a$). The centrifugal force is given by

$$F = \frac{mV^2}{r} \tag{3-1}$$

Where the centrifugal force (*F*), mass of the particle (*m*), velocity of the particle (*V*) and the radius of the cyclone (*r*) are applicable.

Due to the separation of the particles relying on the mass of the particles, as in equation 3-1, the smaller the particle, the less mass it has and the more difficult it is to remove. Therefore, the efficiency decreases as the particulate size of the pollutant decreases, as seen in Figure 5. This is known as Lapple's efficiency curve (Schnelle & Brown, 2000).

This efficiency is based on Lapple's efficiency correlation as indicated in equation 3-2 (Schnelle & Brown, 2000).

$$\eta_j = \frac{1}{1 + \left(\frac{d_{p50}}{d_{pj}}\right)^2} \tag{3-2}$$

3.2.3 Electrostatic Precipitators (ESP)

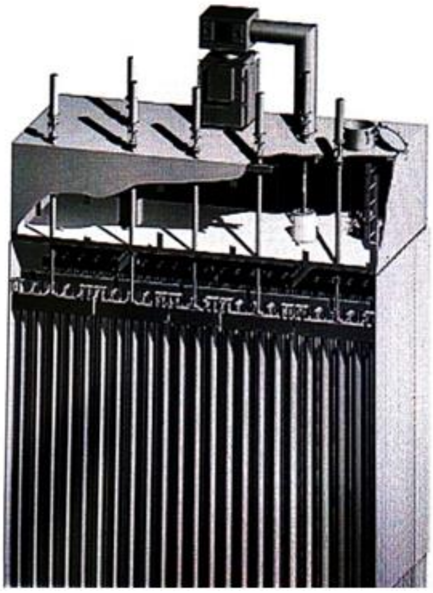
Dry ESP's are typically used to remove the particulate from the following applications which emit flue-gas exhaust gas (Schifftner, 2002):

- Cement production kilns
- Power station boilers
- Paper production mills
- Metal processing and production plants

- Glass production furnace
- Similar industrial applications

The basic operation principal of an ESP is to generate an electrostatic field around a set of collection plates, which can be seen in Figure 7. When the carrier gas enters the ESP, the particulate is charged by a corona discharge (Schifftner, 2002). Negatively charged ions and electrons are contained within the corona, which is effectively plasma. These ions and electrons attach themselves to the particles, thus charging the particles negatively. As the carrier gas passes through the ESP, the negatively charged particles are attracted to the positively charged collection plates, and become attached to the plates.

To remove the collected particles, the ESP makes use of a mechanical "hammer" which raps the collection plates. This impact on the plates loosens the particles, which then falls to the base of the ESP where it is deposited through a hopper into a bin.



3-1: Single field electrostatic precipitator (Schifftner, 2002)

3.3 Scrubber Selection

Once the possible scrubber solutions have been assessed an applicable candidate needs to be selected. There are a variety of aspects that need to be considered during the selection process, each of which are weighted dependent on the end-user preference, national legislation and industrial position. It is very difficult to determine these weights prematurely, as these influences can alter the final outcome of the selection.

For an accurate selection to be done, an experimental phase needs to be initiated to determine a baseline, and then select possible solutions based on the results. Once the experiments are complete, the possible solution may vary significantly from the candidates discussed in this section.

4 Industrial Application

An electric arc-furnace in the industry requires a primary off-gas scrubbing system to be designed and implemented. The furnace characteristics are indicated in table 4-1.

Table 4-1: Physical characteristics of the furnace

Furnace Physical Characteristics	
Description	*Type*
Furnace Type	Enclosed submerged arc furnace
Process Type	Reduction process
Products	Ferromanganese
Furnace Load	42MW, 65 MW maximum
Transformer Rating	81 MVA
Reductant	60% Ore, 40% Coke
Operation	Continuous (24 hours per day, 365 days per year)

The furnace is enclosed to prevent the escape of gases from the process. A sealed system is critical to contain thermal energy for process optimization, as well as being a legal requirement concerning emission laws. Being a submerged arc process, the ore and reductant are mixed before charging the furnace. The electrodes are submerged in the charge material, and the new cold-charge forms a layer on top of the molten bed, which contributes towards the containment of thermal energy.

Table 4-2: Assumed furnace off-gas properties

Off-Gas Properties	Average		Maximum		Minimum	
	Value	*Unit*	*Value*	*Unit*	*Value*	*Unit*
Volume	23 524	Nm^3/hr	40 000	Nm^3/hr	0	Nm^3/hr
Temperature	550	*°C*	900	*°C*	Ambient	-
Inlet Dust Loading	50	g/Nm^3	150	g/Nm^3	20	g/Nm^3
Particle Size Distribution	30	*µm*	300	*µm*	0.3	*µm*
Required Outlet Emissions	-	-	<30	mg/Nm^3	-	-

The off-gas properties of the furnace process are assumed, and therefore need to be verified through experimentation. The furnace is assumed to yield an average of 23,524 Nm^3/hr with a dust load of approximately 50 g/Nm^3, as indicated in table 4-2.

Table 4-3: Assumed primary off-gas composition

Furnace Primary Off-gas Composition				
Composition	*Target*		*Range*	
Carbon monoxide (CO)	60.0	%	50.0 – 70.0	%
Carbon dioxide (CO_2)	16.0	%	10.0 – 25.0	%
Oxygen (O_2)	0.5	%	0.0 – 2.0	%
Hydrogen (H_2)	10.0	%	4.0 – 25.0	%
Methane (CH_4)	1.2	%	0.5 – 4.0	%
Nitrogen (N_2)	9.6	%	*Balance*	

The off-gas composition of the furnace process is assumed, and needs to be verified though experimentation. Each gas within the composition fluctuates during the reduction process, as indicated in table 4-3, and therefore an average needs to be determined for design purposes.

4.1 Process Overview

This study will focus primarily on cleaning the primary off-gas of a ferromanganese electric arc furnace in the industry. Therefore, the environmental impact concerned will be that of air quality. This poses a complex analysis of a significant amount of data and information involved in this unique field of study; the outcome, however, will be directly beneficial towards the environment, which ultimately benefits mankind.

The design of a gas cleaning system for any application requires an in-depth knowledge of the process involved before and after the cleaning of the gas. There are similarities between gas cleaning systems in different applications which can be considered constants. This study, however, will assess the process before, during and after the gas cleaning system so that each stage of the process can be fully understood. This knowledge can then be applied to design a gas cleaning system in an application different to that of this study.

The complete cycle of the gas is indicated in Figure 4-1 below, which is the basis of this study. Each stage will be researched and discussed in detail, which will then lead to a detailed design of a gas cleaning system for the application.

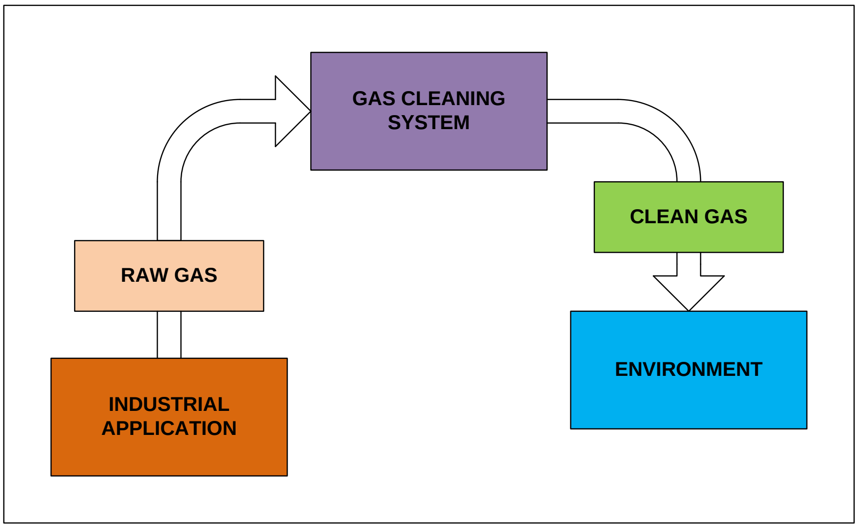


Figure 4-1: Gas cycle of an industrial application process

The gas cycle gas can be broken down into three stages:

1. **Application** - refers to the process that generates the raw gas.
2. **Gas cleaning system** - process that cleans the raw gas by removing particulate
3. **Environment** - space that the gas occupies after being discharged

Due to the nature of this study, the most relevant legislation is The Air Quality Act. This act is formally called National Environmental Management: Air Quality Act 39 of 2004.

The act defines air pollution as the change in composition of air which contains smoke, soot, dust including fly-ash, cinders or any type of solid particles, gases, fumes, aerosols and odorous substances.

4.2 Basic Furnace Operation

It is important to understand the basic operation of a furnace, so that the requirements for the primary off-gas cleaning system can be correctly interpreted. Figure 4-1 depicts the basic gas cycle for the usual application and process, however the cycle must now be detailed for a better understanding of the overall process from start to finish.

Once the overall process and application is understood, literature can then be applied as to what type of cleaning system must be selected. This is the start of the primary off-gas cleaning system design, because the correct selection of gas cleaning system is the first step in research for the solution to the client requirements and specifications.

Figure 4-2 indicates a more detailed gas cycle process in the ferromanganese electric arc-furnace, with detailed descriptions to follow.

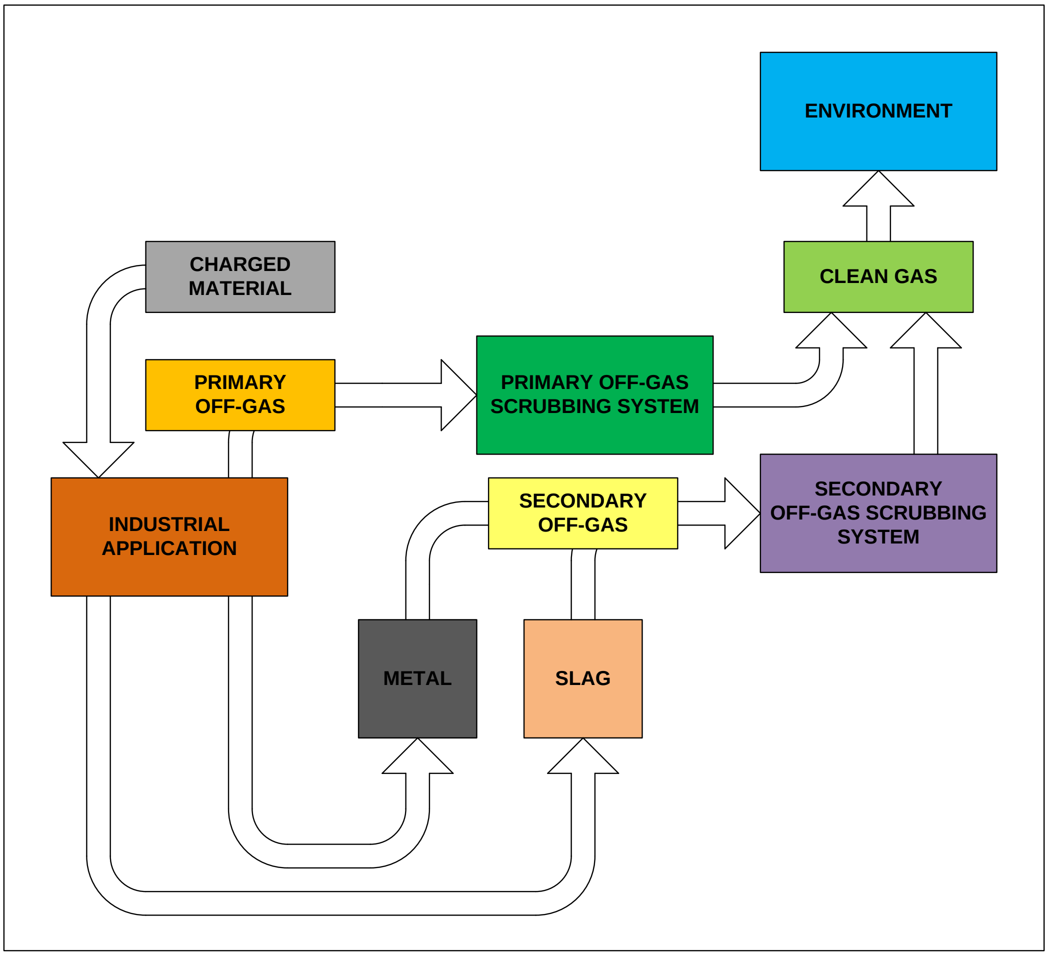


Figure 4-2: Detailed gas cycle of a ferromanganese electric arc-furnace

Each component in Figure 4-2 needs to be considered when designing a new system, regardless of how minor its impact. The tiniest component can often govern an outcome, which requires diligent design and consideration. Each of the following components are critical during the evaluation stage of a system, and need to be fully comprehended before proceeding:

Charged material - This is the absolute start of the process. The charged comprises of a mixture of ore and reductant, which is distributed evenly into the furnace. The furnace electrodes are always submerged, close to the furnace floor. An electric current is induced through the electrodes into the charged material, which sustains the reduction process. Inside the furnace there are three relevant components:

- Cold reductant, at the top of the furnace, which has not yet started to reduce
- Hot reductant, at the bottom of the furnace, which consists of both slag and metal. The slag is less dense, and thus separates at moves upwards from the denser metal.
- Off-gas which is generated by the process

Furnace - This is the vessel in which the smelting process takes place. The interior of the furnace is lined with thick refractories, which protect the outer steel shell from the immense heat generated during the process.

Primary off-gas - The primary off-gas is a by-product of the process over and above the metal and slag. The composition of this gas is indicated in table 4-3, and particulate matter is also present in the gas.

Primary off-gas scrubbing system - This is the system which cleans the gas, by removing a predetermined percentage or mass of particulate matter. The client specifications in table 4-3 indicate that a maximum of 30 mg/Nm^3 is allowed to be emitted into the atmosphere. This is the primary focus of this study.

Metal and slag - The tapping takes place once the charged material has been reduced. Due to the metal being at the bottom it is tapped first; either into a casting pot or casting bay, where it is processed further. Once all the metal has been tapped from the furnace, the layer of slag moves downwards to replace the void where the metal resided. The slag is then tapped from the furnace on the opposite side from where the metal is tapped; also into a slag pot or slag bay.

Secondary off-gas - Due to the extreme heat of the metal and slag, there is a lot of energy within these products. When they are tapped, the total surface area of the metal or slag increases, allowing the energy to be released in the form of dust and particulate matter.

Secondary off-gas scrubbing system - The fumes and dust released during tapping also contributes towards the total emissions of the furnace. Therefore, the secondary off-gas stream also needs to be cleaned. This is not, however, the focus point of the study; the design criteria and client requirements and specifications are very different to that of the primary off-gas scrubbing system.

Clean gas - This is the ultimate product of the gas cycle in this process. The clean gas which is emitted, from both the primary and secondary off-gas cleaning systems, is measured to determine the final particulate emission of the process. This data is then submitted in a report to the provincial environmental department, as per Section 30 of the National Environmental Management: Air Quality Act 39 of 2004.

Environment - The environment is ultimately what we strive to protect and preserve, as we have a moral responsibility towards environmental conservation. Legislation and penalties should not be the motivation for conforming to environmental conservation standards; the motivation should be to preserve the earth which we have inherited. We only have one opportunity to prevent global environmental disintegration.

4.3 Ferromanganese Smelting Process

Before any attempt is made to initiate a concept design, it is important to understand the ferromanganese smelting process, and evaluate it from first principals. By doing so, all assumptions can be eliminated and a solution can be designed without compromising accuracy.

4.3.1 Background of the Smelting Process

When mined, the raw ingredient is a combination of iron-oxide and manganese-oxide. The presence of these two molecules in the ore can be described as

$$Fe_2O_3 + MnO_2$$

Due to the presence of oxygen molecules in both the iron- and manganese-oxides, it is a norm in the industry to subject the ore to a high temperature in the presence of carbon, a reductant, known as a reduction process. The reduction process reduces the iron- and manganese-oxides to ferromanganese, and oxidises the elemental carbon. Insufficient oxygen atoms results in the carbon undergoing partial oxidation and forming carbon monoxide which consists of two covalent bonds and one dative covalent bond (Thompson, 2005). The mass balance in for this process is indicated in equation 4-1.

$$Fe_2O_3 + MnO_2 + 7C = 2FeMn + 7CO \tag{4-1}$$

When considering the production of ferromanganese in an electric arc furnace, a lot of attention needs to be focused on the energy consumption which is dependent on the availability of oxygen in the ore, and the reductant used. The Boudouard reaction is the primary focus when considering energy consumption of the process, which is indicated in equation 4-2.

$$CO_2 + C = 2CO \qquad (4\text{-}2)$$

4.3.2 Ferromanganese Production

The most commonly produced manganese containing ferroalloy is high carbon (HC) ferromanganese, which is produced either in a blast furnace or electric arc furnace (Tangstad & Olsen, 1995). Medium carbon (MC) ferromanganese is produced by subjecting the HC ferromanganese to an oxygen stream at high temperatures. This further oxidises the remaining carbon bound in the molten HC ferromanganese, thus reducing the carbon content. MC ferromanganese is a higher grade than HC and has increased costs to produce. Its production is therefore solely dependent on market prices.

Electric arc furnaces are more flexible than blast furnaces, as the slag can be further processed refined ferromanganese. Reductant and electricity prices also dictate the type of process selected for the reduction process.

4.3.3 Process Chemistry

A layout of a typical electric arc furnace is illustrated in Figure 4-2, indicating the molten bed of the furnace, as well as the upper, cooler charge. The temperature in the cold charge layer ranges from 200 to 250°C. The charged material contains ore, reductant, flux in the form of carbonates, limestone and quartzite.

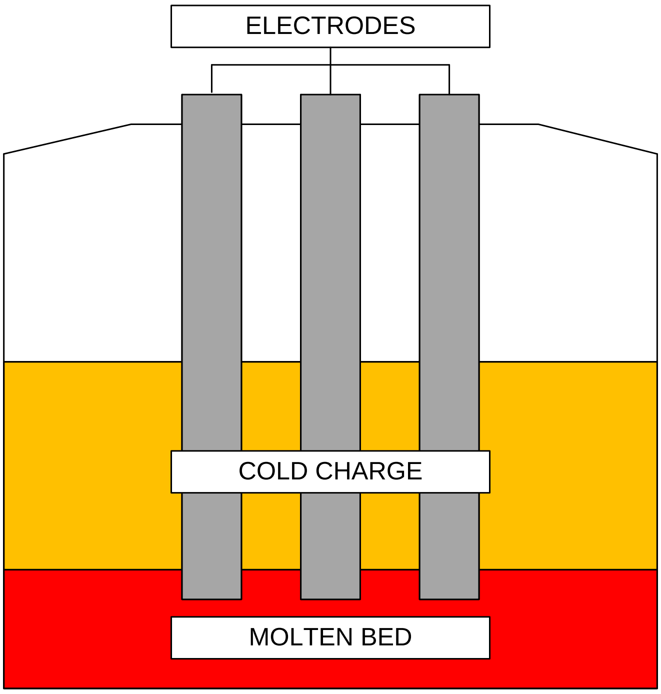


Figure 4-3 : Section view of a closed electric arc furnace with the molten bed and cold charge layers

Evaporation of water takes place in the cold charge layer, which is considered in equation 4-3.

$$H_2O_{(l)} = H_2O_{(g)} \qquad \Delta H^0_{298} = 44\ kJ/kmol \qquad (4\text{-}3)$$

At temperatures below 700°C, a portion of the water vapour will react according to equation 4-4, as there is always hydrogen present in the furnace off-gases.

$$H_2O_{(g)} + CO_{(g)} = H_{2(g)} + CO_{2(g)} \qquad \Delta H^0_{298} = -41.1\ kJ/kmol \tag{4-4}$$

Another source of hydrogen is from Faraday's principle of electrolysis, which is the decomposition of water into hydrogen and oxygen gas. The presence of massive electric current being passed through the charge material is ideal for the reaction to take place, as indicated in equation 4-5. A third source of hydrogen is the volatiles in the reductant.

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)} \qquad \Delta H^0_{298} = -286\ kJ/kmol \tag{4-5}$$

The carbonates which are added to the charge in the form of $MgCO_3$ and $CaCO_3$ start to decompose at 400°C and 900°C respectively, and is indicated in equation 4-6 and 4-7.

$$MgCO_3 = MgO + CO_{2(g)} \qquad \Delta H^0_{298} = 101.1\ kJ/kmol \tag{4-6}$$

$$CaCO_3 = CaO + CO_{2(g)} \qquad \Delta H^0_{298} = 178.3\ kJ/kmol \tag{4-7}$$

The manganese ores contain alkali oxides, Na_2O and K_2O, which are reduced to metal vapour when in the molten bed. These vapours then follow the gas stream to the cold charge layer where they oxidise to form alkali carbonates, as indicated in equation 4-8.

$$2K_{(g)} + 3CO_{(g)} = K_2CO_{3(l)} + 2C \qquad \Delta H^0_{298} = -1\ 010\ kJ/kmol \tag{4-8}$$

As these alkalis circulate, heat is transferred from the molten bed to the cold charge layer, assisting with pre-reduction and pre-heating of the charge material.

The reduction of manganese ores is a regenerative process, in that it is able to be reduced by both carbon and carbon monoxide. The furnace effectively generates its own reductant once the smelting process has reached a certain temperature.

Higher manganese oxides are dominant in manganese ores, which benefits the process from an energy consumption approach. The higher oxides, MnO_2, Mn_2O_3 and Mn_3O_4, can be easily reduced with CO, as they are unstable compared to the lower oxides (Tangstad and Olsen, 1995). These reactions are indicated in equations 4-9, 4-10 and 4-11.

$$MnO_2 + \tfrac{1}{2}CO = \tfrac{1}{2}Mn_2O_3 + \tfrac{1}{2}CO_2 \qquad \Delta H^0_{298} = -99.9\ kJ/kmol \tag{4-9}$$

$$\tfrac{1}{2}Mn_2O_3 + \tfrac{1}{6}CO = \tfrac{1}{3}Mn_3O_4 + \tfrac{1}{6}CO_2 \qquad \Delta H^0_{298} = -31.3\ kJ/kmol \tag{4-10}$$

$$\tfrac{1}{3}Mn_3O_4 + \tfrac{1}{3}CO = MnO + \tfrac{1}{3}CO_2 \qquad \Delta H^0_{298} = -16.9\ kJ/kmol \tag{4-11}$$

The reduction of higher oxide manganese is an exothermic reaction, producing a significant amount of heat. This also contributes to the pre-reduction and pre-heating of the charge materials.

Once the furnace temperature has increased to 1000°C, the reaction that takes place on the reductant surface is rapid enough to allow both the ore reduction (4-11) and the Boudouard reaction (4-12) to react simultaneously.

$$\tfrac{1}{3}Mn_3O_4 + \tfrac{1}{3}CO = MnO + \tfrac{1}{3}CO_2 \qquad \Delta H^0_{298} = -16.9\ kJ/\ kmol \tag{4-11}$$

$$\frac{1}{3}C + \frac{1}{3}CO_2 = \frac{2}{3}CO \qquad \Delta H^0_{298} = +57.5\ kJ/kmol \tag{4-12}$$

$$\frac{1}{3}Mn_3O_4 + \frac{1}{3}C = MnO + \frac{1}{3}CO \qquad \Delta H^0_{298} = +40.5\ kJ/kmol \tag{4-13}$$

Due to the presence of iron in the manganese ore, the reduction of the iron oxides reacts concurrently with the manganese oxide reduction. The following reactions take place:

$$\frac{1}{3}Fe_3O_4 + \frac{4}{3}CO = Fe + \frac{4}{3}CO_2 \qquad \Delta H^0_{298} = -4.5\ kJ/kmol \tag{4-14}$$

$$\frac{1}{3}Fe_3O_4 + \frac{4}{3}C = Fe + \frac{4}{3}CO \qquad \Delta H^0_{298} = +225.4\ kJ/kmol \tag{4-15}$$

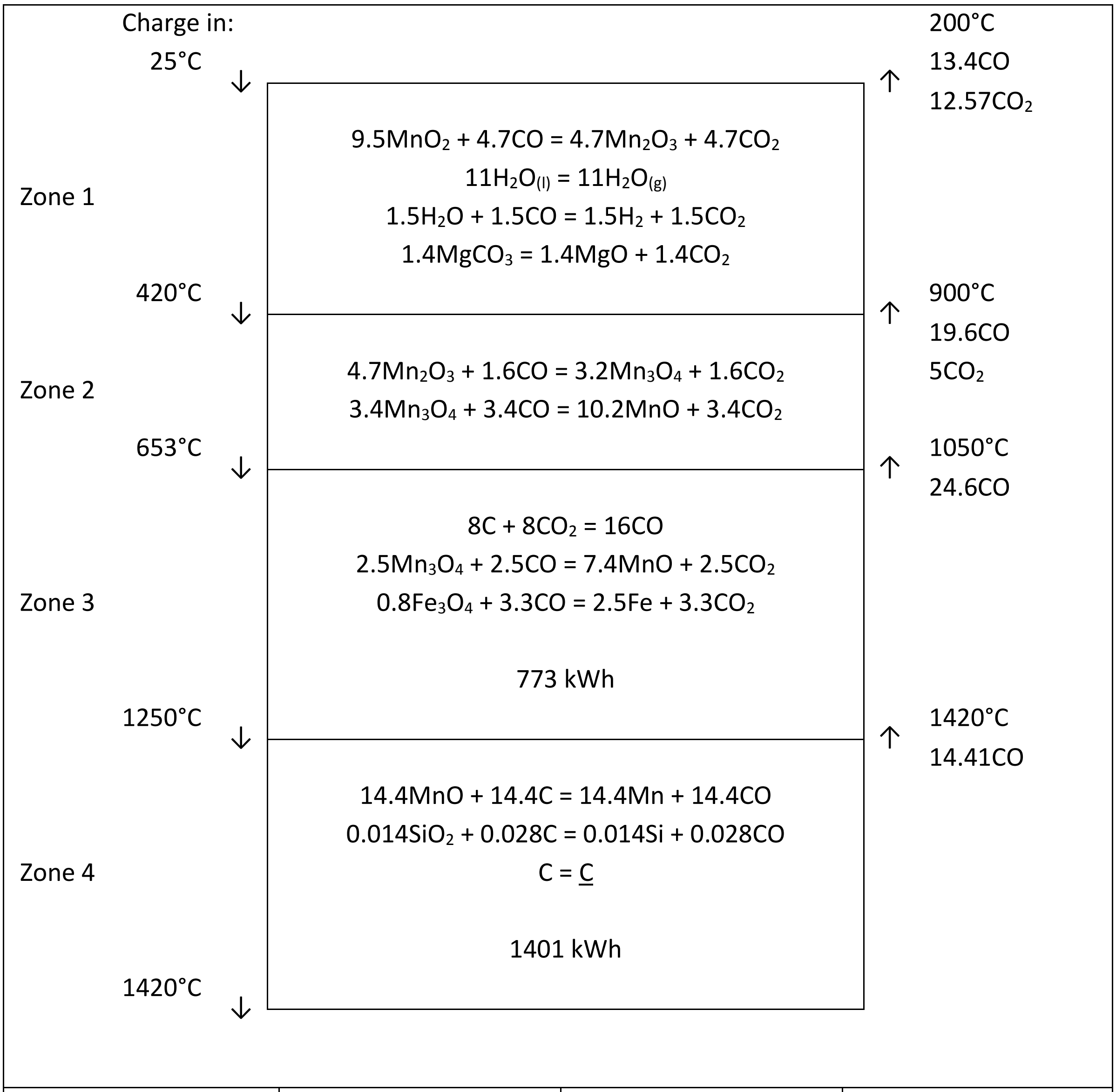
$$MnO_{(l)} + C = Mn_{(l)} + CO_{(g)} \qquad \Delta H^0_{298} = +246.8\ kJ/kmol \tag{4-16}$$

$$SiO_{2(l)} + 2C = Si_{(l)} + 2CO_{(g)} \qquad \Delta H^0_{298} = -286\ kJ/kmol \tag{4-17}$$

$$K_2CO_{3(l)} + 2C = 2K_{(g)} + 3CO_{(g)} \qquad \Delta H^0_{298} = -286\ kJ/kmol \tag{4-18}$$

Four zones can be described when considering the ore reduction process, which is indicated in Figure 4-3. These zones are temperature dependant and induce different reactions and mass balances, which are as follows:

Zone 1:	**Drying and calcination**	Reduction at low temperatures, MnO_2 → Mn_2O_3
Zone 2:	**Gas reduction**	Reduction of manganese-oxide, Mn_2O_3 → Mn_3O_4 and partial MnO
Zone 3:	**Direct reduction**	Reduction of iron-oxide, Fe_3O_4 → Fe
Zone 4:	**Smelting reduction**	Partial reduction of MnO to liquid metal



Charge in	Off-gas (dry)	Slag	Metal
MnO_x (x = 1.7) 17.57 kmol Mn Dolomitic limestone 10% H_2O 339 kg C	5% H_2 49% CO 46% CO_2	33% MnO 11% Al_2O_3 18% CaO 26.8% SiO_2 8% MgO 2.3% K_2O Balance ≈ 2%	79% Mn 14% Fe 7% C 0.04% Si

Figure 4-4 : Staged heat belance and material balance for a ferromanganese reduction process (Tangstad and Olsen, 2005)

In a scenario where the production of one ton of HC FeMn is required, the raw materials are combined with compositions as in Figure 4-3 to produce the metal, slag and off-gas. The molten metal and slag has a temperature of 1420°C; therefore the off-gas generated has the same temperature. The off-gas enters zone 1 with an assumed temperature of 900°C, which is ideal for drying the cold charge and decomposing the $MgCO_3$ (Tangstad and Olsen, 2005).

It is a near impossible calculation to determine the exact off-gas temperature above the cold charge in a furnace at any given time. This varies with the depth of the cold charge, the size of the charge material, the heat transfer coefficient of the ore which is composition dependent, and the stability of the reduction process. Eruptions within the furnace can cause the off-gas temperature to spike instantly, exceeding 1000°C. An assumption can be made that the maximum and minimum off-gas temperatures are 900°C and 200°C respectively, resulting in an average of 550°C, which will be used to initiate the off-gas calculations. This value will, however, require experimental confirmation to ensure that the most accurate value is used as a design base.

The ratio of CO_2 to CO + CO_2 is a function of the carbon consumed by the reduction process. It is favourable towards the reduction process for a greater presence of CO, as described in equation 4-11, however the yield of CO is dependent on the energy input into the furnace, as illustrated in Figure 4-5. The energy consumption is a direct cost for ferromanganese production and there exists a trade-off between energy input and CO reduction energy saving, however they are ultimately governed by the carbon consumption, which is also a direct cost of production.

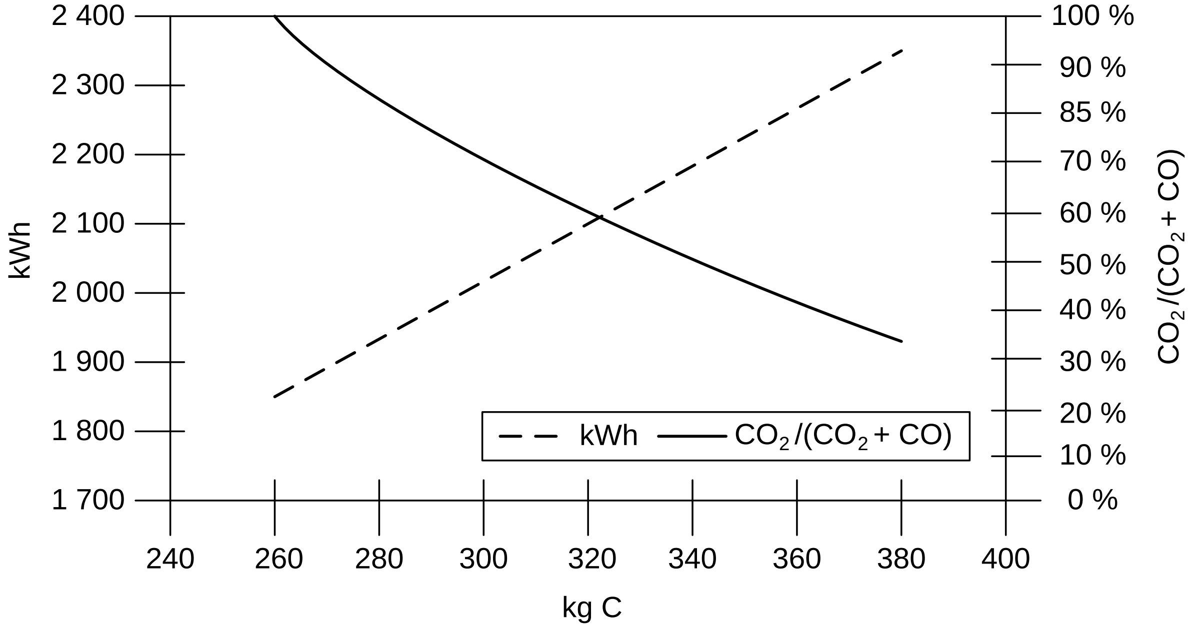


Figure 4-5 : Energy consumption vs. carbon consumption vs. the ratio of CO_2 to total off-gas (Tangstad and Olsen, 2005)

5 Pre-Design Experimentation

To initiate a preliminary design it is important to have values that are as accurate as possible to minimise errors, which can result in an inefficient or unsuitable solution for the application. It is commonplace in the industry for a client to conduct experiments before approaching consultants for an engineered solution, so that a baseline can be established. This saves both time and money when engineering a solution, however the following occurrences are most common:

- Inaccurate experimental results due to:
    - Incorrect sampling techniques
    - Inaccurate calibration of sampling equipment
    - Inadequate steps taken to preserve physical samples
    - Incorrect testing methods applied at the laboratory
- Unstable furnace conditions during sampling resulting in inconclusive results
- Changes in furnace operating parameters during sampling, such as a change in the charge material smelting recipe
- Incorrect standards used for conducting experiments

It is critical to establish a reliable set of standards and experimenting criteria beforehand, so as to eliminate inconsistencies and conclude a reliable baseline.

5.1 Critical Data

There is an immense amount of information that can be collected from any process. The first step in initiating the experimentation is to identify which information in relevant, and conduct the applicable experiments. Experimentation is costly and timeous; it is wise to collect the least amount of data necessary, without compromising accuracy and quality. Table 5-1 indicates typical data that is necessary to design a gas scrubbing system, along with a motivation as to why it is relevant.

Table 5-1: Necessary data required for designing a scrubber system

Input Component	Relevance
Gas temperature	• Type of cooling system is dependent on the inlet gas temperature • Governs material selection for the components • Critical for calculating an accurate actual gas flow rate
Gas pressure	• Governs material selection for the components • Critical for calculating an accurate actual gas flow rate
Gas composition	• Heat transfer is a function of each present gas • Type of neutralising system is dependent on the gas composition • Critical for stoichiometric calculations • Necessary for safe operating procedures to be generated
Particulate in the gas stream	• Type of scrubbing system is dependent on the particle size distribution • Scrubber efficiency is a function of the particle size distribution

5.2 Sampling

Each component requires a specialized method of sampling to achieve accurate results. These components can have adverse effects on the environment, which has forced legislation to strictly monitor the sampling methods and maintain a standard to ensure consistency, i.e. two different instruments sample under the same conditions and return results within an allowable tolerance.

5.2.1 Gas Temperature

5.2.1.1 Sampling Method

For a reliable data series, the furnace off-gas temperature needs to be monitored continuously over a period of time at full power load. This will give an accurate representation of a mean temperature value, as well as temperature spikes as a result in unstable smelting conditions.

The intense heat within the furnace demands a sampling instrument capable of high operating temperatures, typically a high grade thermocouple. A Type-K thermocouple is capable of operating in temperatures exceeding 1000°C, which is in excess of the off-gas leaving Zone 2 as indicated in Figure 4-4.

The location of the instrument is critical for reliable data collection. When the furnace is charged, the material is not always distributed evenly, which causes the height of the cold charged material in the furnace relative to the bed varies. When the off-gas passes through a larger material height, more heat is transferred, cooling the gas further. The opposite is true when the gas passes through less height of material. To account for these possible differences, three thermocouples are used to sample instead of one, as indicated in Figure 5-1. An average is then taken between the three thermocouples, and this is used to determine a baseline for the standard operating temperature. The thermocouples are located on the furnace roof, as this is the applicable gas temperature required for the scrubber.

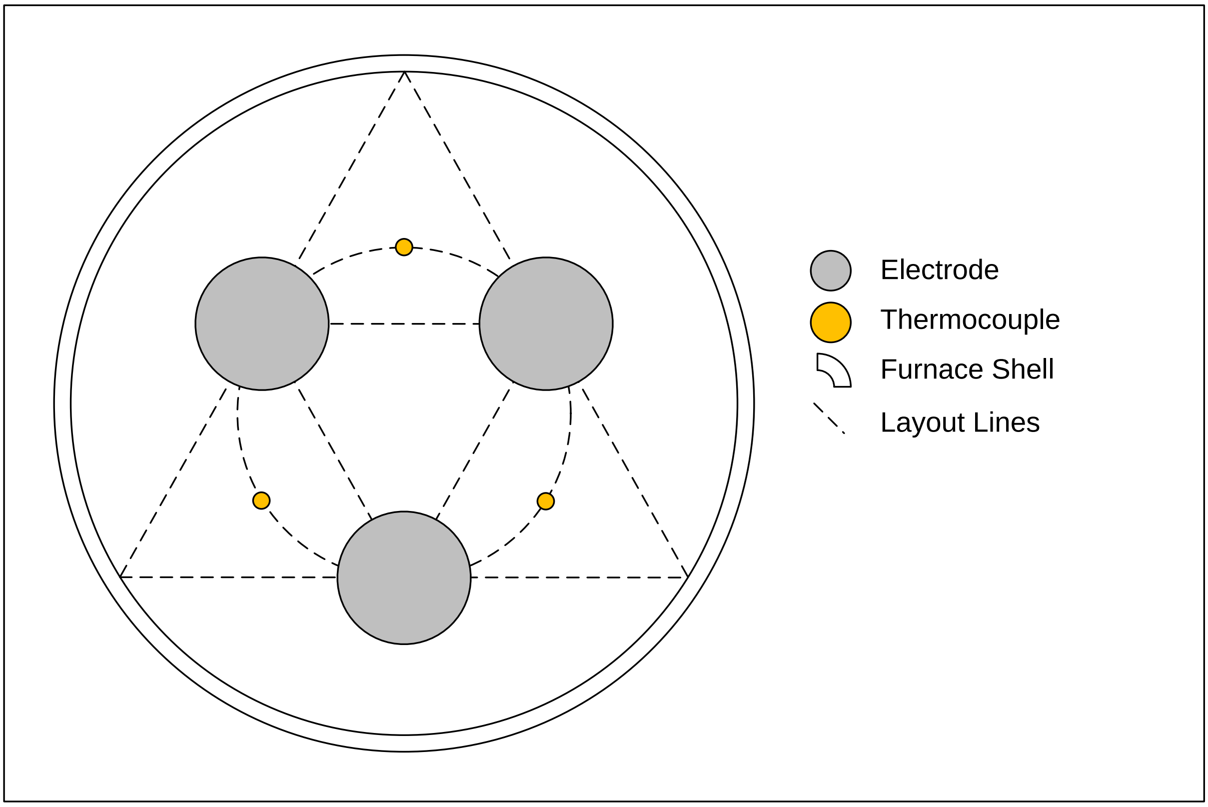


Figure 5-1: Layout of the thermocouples on the furnace roof relative to the electrodes

Data is collected for a period of 5 days at intervals of one hour to monitor the conditions in the furnace as extensively as possible. During this period data during upset conditions is also collected, however this does not occur often. These temperature spikes are still relevant as they must be taken into account when selecting the construction material and to design for the necessary safety precautions to protect the equipment.

5.2.1.2 Results

The results were conclusive, as indicated in table 5-2. The average gas thermal properties are determined and used as the baseline for the design.

Table 5-2: Furnace temperature values

Furnace Temperature	
Description	Temperature *[℃]*
Average	310.50
Maximum	497.90
Minimum	244.00
Standard deviation	62.80

The values in table 5-2 are sufficient for the purpose of initiating design calculations. The data series incorporates both a good average and visible minimum and maximum values. The average temperature will be used to design for a constant operating temperature, whereas the minimum values will be used to design safety features. There is a clear trend in Figure 5-2 of the furnace temperature over time; this varies, as it is a highly reactive environment.

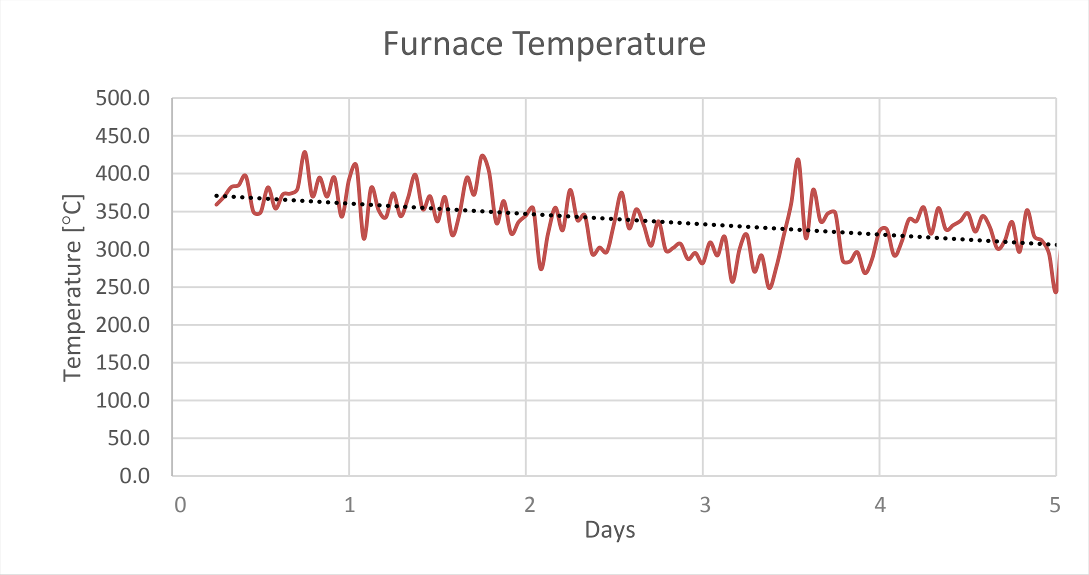


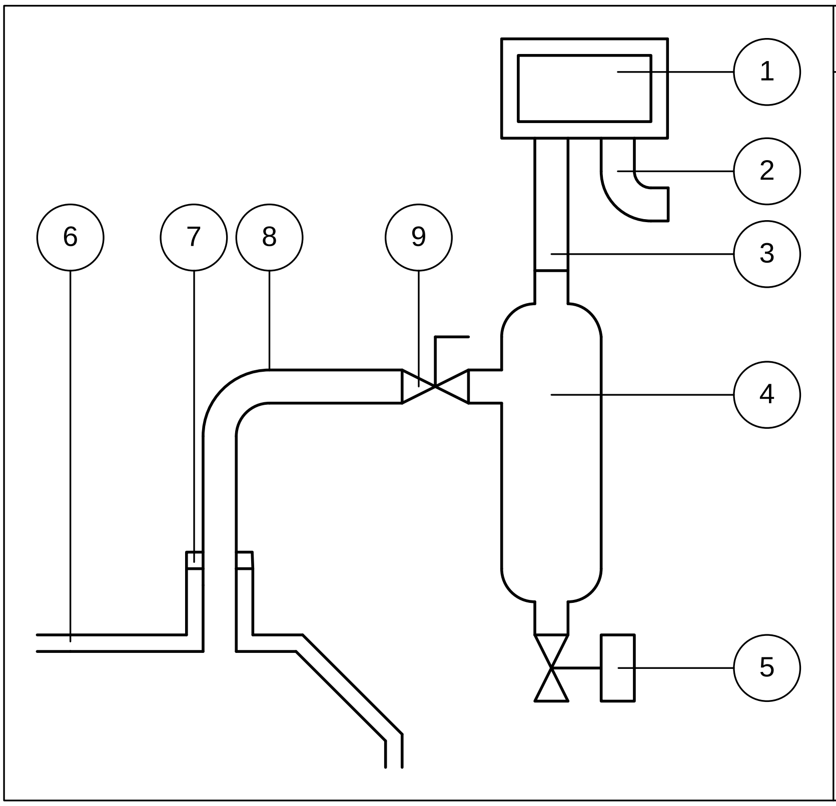
Figure 5-2: Furnace temperature over a period of five days

5.2.2 Gas Pressure

5.2.2.1 Sampling Method

Furnace pressure is one of the most important control points on a furnace. Excessively low furnace pressure results in a vacuum within the shell, inducing air ingress which can cause an explosion if the correct stoichiometric ratio is achieved. Excessively high furnace pressure allows gas to escape to the surrounding atmosphere, which then combusts and can damage the equipment in the surrounding area. The pressure needs to be controlled very accurately and responsively to ensure safe operation at all times. Furthermore, the gas pressure is used along with the gas temperature to determine the density, which is critical when selecting gas displacing equipment (fans, compressors, etc.).

A differential pressure transmitter is used to continuously measure the internal furnace pressure over a period of time. The transmitter measures the difference between the internal and atmospheric pressure, as this is the relevant control parameter. Figure 5-3 indicates the configuration of the transmitter.



Components

- **1** – Pressure transmitter
- **2** – Atmospheric sampling inlet
- **3** – Furnace sampling inlet
- **4** – Moisture catch-pot
- **5** – Auto drop-out valve
- **6** – Furnace roof
- **7** – Heat resistant seal
- **8** – Take-off pipe
- **9** – Maintenance shut-off valve

Figure 5-3: Pressure transmitter arrangement for the furnace internal pressure

5.2.2.2 Results

Upon completing the sampling, a relevant series of data was returned. The typical furnace pressure values indicated in table 5-3. The maximum pressure indicated occurs when the gas yielded is greater than the extraction capacity of the scrubber plant. The opposite is true for the minimum pressure, which occurs when the gas extracted is greater than the furnace yield. Both cases are minimal when considering the process, the leakage inward and outward is a function of the pressure difference, as expressed in equation 5-1, where A_{seal} is the leak area on the furnace roof and Δp is the pressure difference in Pa. The equation returns the result in m^3/s.

$$Q_{leak} = A_{seal}\sqrt{\frac{2p}{\rho_g}} \tag{5-1}$$

Table 5-3: Furnace pressure values

Furnace Pressure	
Description	Pressure [mmH_2O]
Average	0.3
Maximum	6.2
Minimum	-5.2
Standard deviation	3.3

There is a clear trend in Figure 5-4 of the furnace temperature over time.

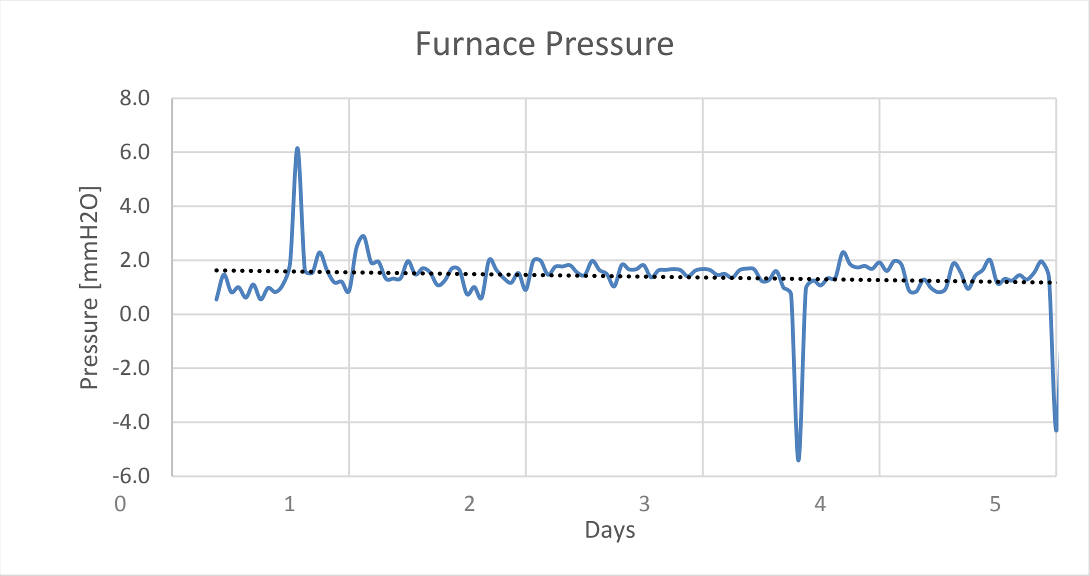


Figure 5-4: Furnace pressure over a period of five days

5.2.3 Gas Composition

5.2.3.1 *Sampling Method*

Isokinetic sampling can be described as the extraction of a gas under normal operating conditions, without altering external influences. Gas is subject to change when it undergoes a change in temperature or pressure; therefore a sampling technique needs to be used in which both the temperature and pressure are identical to the operational properties of the gas stream.

There are many different standards for emission sampling including BS, EN and ISO. For this study the Environmental Protection Agency (EPA) was used to sample the gas stream. There is a large variety of properties that can be measured with a single isokinetic sample, including:

- Temperature
- Pressure
- Mass flow rate
- Particle size distribution
- Particulate properties, i.e. density, composition
- Gas composition
- Volatile measurement

To measure all of these parameters, a reliable sampling system needs to be used in order to extract the gas without changing any external effects. A typical sampling rig is indicated in Figure 5-5.

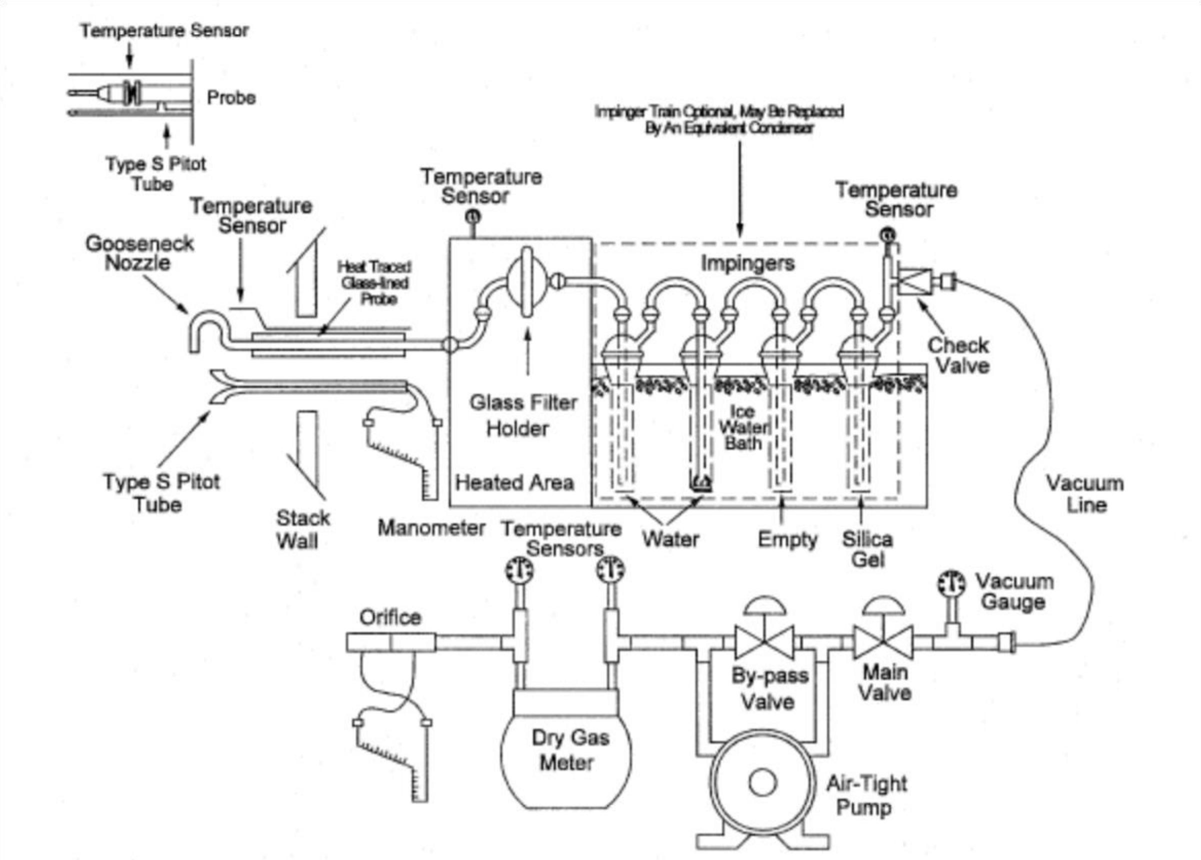


Figure 5-5: Isokinetic sampling rig (Environmental Protection Agency, 2000)

The probe is inserted into the gas stream and sealed off. Turbulence within the duct causes irregular flow patterns which can affect the sampled result. According to the Environmental Protection Agency (2000), the turbulence within the duct needs to be accounted for. There are two requirements according to the EPA which need to be adhered to, namely:

- Sampling needs to be conducted for at least one hour, or one normal cubic metre of gas needs to be extracted

- The sampling technique needs to account for the gas duct geometry

It is important to ensure that the equipment is calibrated, and that sampling is conducted is accordance with the relevant standards. Figure 5-6 and 5-7 indicates the sections that a duct must be divided into for accurate sampling of the gas stream.

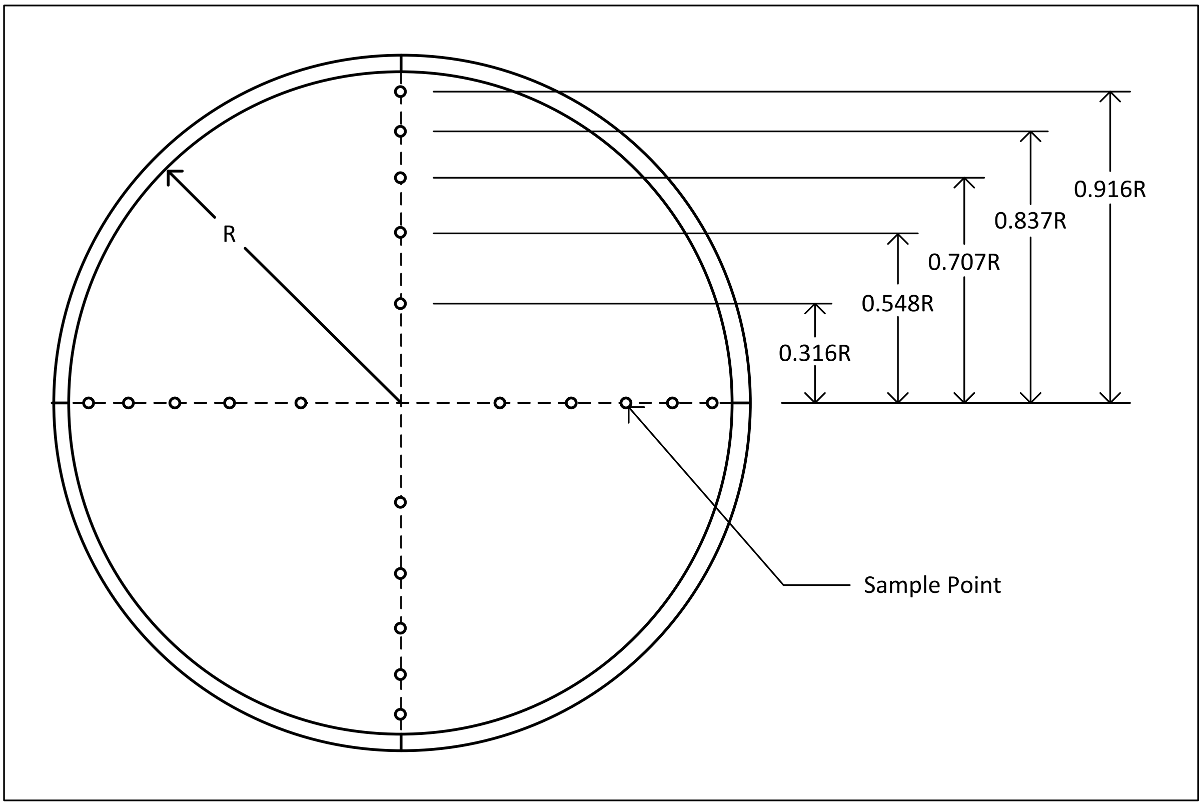


Figure 5-6: Sampling points for a round duct

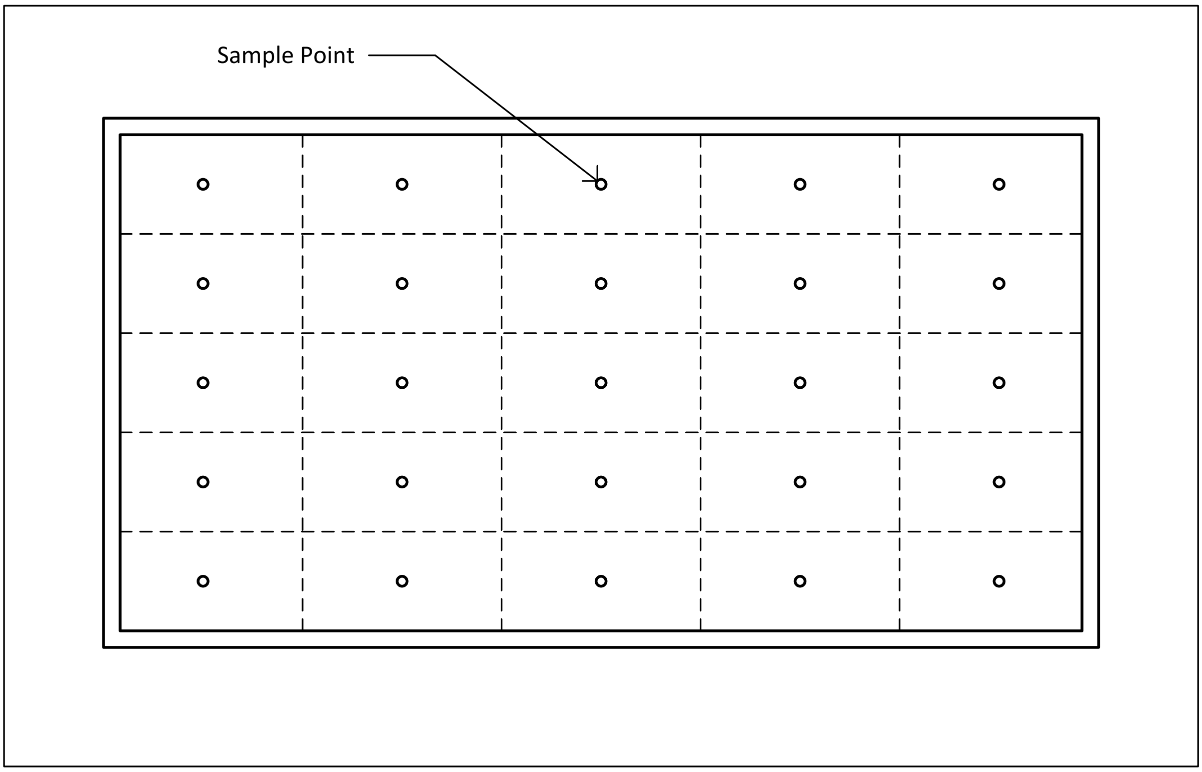


Figure 5-7: Sampling points for a rectangular duct

The sampling rig comprises of a number of different components, indicated in Figure 5-5. A temperature sensor at the front of the probe is used to determine the gas density. A pitot tube measures the dynamic velocity within the duct by applying Bernoulli's law; the volumetric flow rate can thus be determined.

The gas enters the gooseneck nozzle, which is parallel with the flow of gas, and then enters the heated tube. This tube is connected to a fabric filter, which eliminates particulate with a diameter greater than 0.3µm. Both the probe and the filter housing are heated so as to prevent premature condensation of the gas.

Upon leaving the filter area, the gas enters a series of four impingers. These are mounted in an ice bath to force the gas below its dew point. The first two impingers contain water, the third is empty and the last silica gel. The first two impingers make use of the water for the gas to bubble through, encouraging impingement in the water. The third impinger acts as a gravitation separator for the majority of condensation. The last impinger contains a dehydrating agent to eliminate the last of the moisture in the sampled gas stream. All four of these impingers are accurately weighed before the sampling process starts, and then immediately afterwards.

A vacuum pump induces a draft in the rig at a fixed volumetric flow rate, which is measured by the orifice at the pump exhaust. This reading is compared to the flow rate measured in the duct to determine a scale. This is then extrapolated once the laboratory has verified the contents of the filter, impingers and the gas composition.

5.2.3.2 Results

The gas composition results are indicated in table 5-4 by volume.

Table 5-4: Gas composition by volume

Gas Composition			
Description	*Average*	*Minimum*	*Maximum*
Carbon Monoxide	61.24 %	57.8 %	65.9 %
Carbon Dioxide	12.74 %	12.1 %	13.8 %
Hydrogen	9.77 %	8.60 %	11.8 %
Oxygen	1.10 %	0.20 %	1.80 %
Nitrogen	14.4 %	8.70 %	17.6 %
Methane	0.71 %	0.60 %	0.80 %

It is clear from table 5-4 that carbon monoxide is the predominant contributor towards the volumetric composition percentage of the off-gas. CO forms in as partial oxidation in environments with insufficient oxygen to generate carbon dioxide. The typical characteristics include

- Colourless, odourless and tasteless
- Harmful to humans when exposed to concentrations greater than 35 ppm
- Flammable

5.2.4 Particulate Matter in the Gas Stream

5.2.4.1 Sampling Method

The range of particle sizes in the off-gas stream of a furnace is typically very large, which makes it difficult to plot the range. A mathematical function can be used to determine the number frequency, in the form of a log-normal distribution (Hinds, 1999) and is indicated in equation 5-2. The advantage of this function is that it can cover a large range, and does not return negative values.

$$\mathrm{d}f = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(d_p - \bar{d}_p)^2}{2\sigma^2}} \mathrm{d}d_p \qquad (5\text{-}2)$$

To sample the gas stream for particulate matter, the same isokinetic rig is used as described earlier, however the tests in the laboratory are significantly different. A laser diffraction technique is used, in which a laser pattern is passed through a particle to measure its geometrical dimension. This technique is not a function of flow rate, i.e. it is not time based (De Boer, 2002).

The particulate was sampled at different furnace loads so as to determine the influence of power input versus dust yield. The dust loading at the different power loads are indicated in table 5-5.

Table 5-5: Furnace power versus dust yield

Dust Yield				
Furnace Power [MW]	Sample 1 [mg/Nm^3]	Sample 2 [mg/Nm^3]	Sample 3 [mg/Nm^3]	Avg. Dust Yield [mg/Nm^3]
6.2	182.64	211.36	209.41	**201.14**
9.0	1 725.16	1 575.46	1 581.16	**1627.26**
15	2 012.17	3 204.22	-	**2608.20**
30	13 956.80	15 337.41	12 399.83	**13 898.01**
42	30 450.41	45 099.84	-	**37 775.13**

Table 5-6: Furnace power versus particle size distribution

Particle Size Distribution					
Furnace Power [MW]	*< 1 µm [per Nm^3]*	*1 µm – 2 µm [per Nm^3]*	*2 µm – 5 µm [per Nm^3]*	*5 µm – 10 µm [per Nm^3]*	*> 10 µm [per Nm^3]*
6.2	0.92 %	11.92 %	62.99 %	22.33 %	1.84 %
9.0	2.15 %	14.24 %	41.98 %	26.80 %	14.84 %
15	3.78 %	22.06 %	46.76 %	19.56 %	7.84 %
30	2.13 %	18.48 %	48.74 %	21.91 %	8.74 %
42	2.60 %	20.34 %	45.51 %	22.86 %	8.68 %

The values in table 5-5 are measured in *mg/Nm^3*, which can be described as a unit scalar. This needs to be converted to *mg/Am^3* and then multiplied by the average dust yield. This will then return the total dust yield per second of the furnace and will be used to calculate the values for the scrubber design.

Table 5-6 indicates the particulate collected from the gas stream in different particle diameter ranges. These values are critical when designing the scrubber, as the collection efficiency is proportional to the particle size distribution; this will be discussed in depth in section 7.

Equation 5-3 returns the collection efficiency of a scrubber, where ψ represents the inertial impaction parameter (Spellman & Whiting, 2005). The inertial impaction parameter in equation 5-4 is a function of the particle diameter d_p and particle density ρ_p; mathematically the efficiency is proportional to these two parameters. The composition of the particulate is required to determine the particle density, and is indicated in table 5-7.

For the purpose of this study, only the operational power input of 42MW will be used to determine the actual volumetric flow rate of the gas, as this is the highest dust yield. The scrubber plant will be designed to eliminate this value of dust; the design approach in section 7 will take the particle size distribution into account where the effect of the PSD on the efficiency is greatest.

$$\eta = 1 - e^{(-kR\sqrt{\psi})} \tag{5-3}$$

$$\psi = \frac{d_p^2\, \rho_p\, V_t}{9\, \mu_g\, d_l} \tag{5-4}$$

Table 5-7: Particulate composition

Particulate Composition		
Element	Percentage *[mass]*	*Density* *[g/cm^3]*
Fe	0.8 %	7.874
Mn	30.5 %	7.210
S	28.2 %	2.070
C	40.5 %	1.900
Total	**100.0 %**	

The gas yielded as a function of furnace power input was sampled, and is indicated in table 5-8.

Table 5-8: Gas yield as a function of furnace power input

Gas Yield			
Furnace Power *[MW]*	Gas Yield *[Am^3/s]*	Temperature *[℃]*	Gas Yield *[Nm^3/s]*
6.2	3.09	390.80	1.271
9.0	4.89	433.60	1.889
15	8.77	440.00	3.359
30	10.57	444.00	4.025
42	11.89	466.00	4.393

5.2.4.2 Dust Load Forecast

When a concept design is underway for a scrubber system, no all the furnace data is available. Usually a furnace construction project entails all the services to build concurrently to ensure that production can commence as early as possible. Therefore, a method was derived by using a curve-fitting tool in Matlab to determine the relationship between furnace power input and dust yield. The plotted values are indicated in Figure 5-8, and the yield rate is defined in equation 5-5.

$$Y = A_e k P^{2.87}$$

(5-5)

Where:

Furnace Power	**P**	is in *MVA*
Dust Yield Rate	**Y**	is in *mg/s*
Electrode Area	**A_e**	is in *m^2*
Constant	**k**	is 0.02032

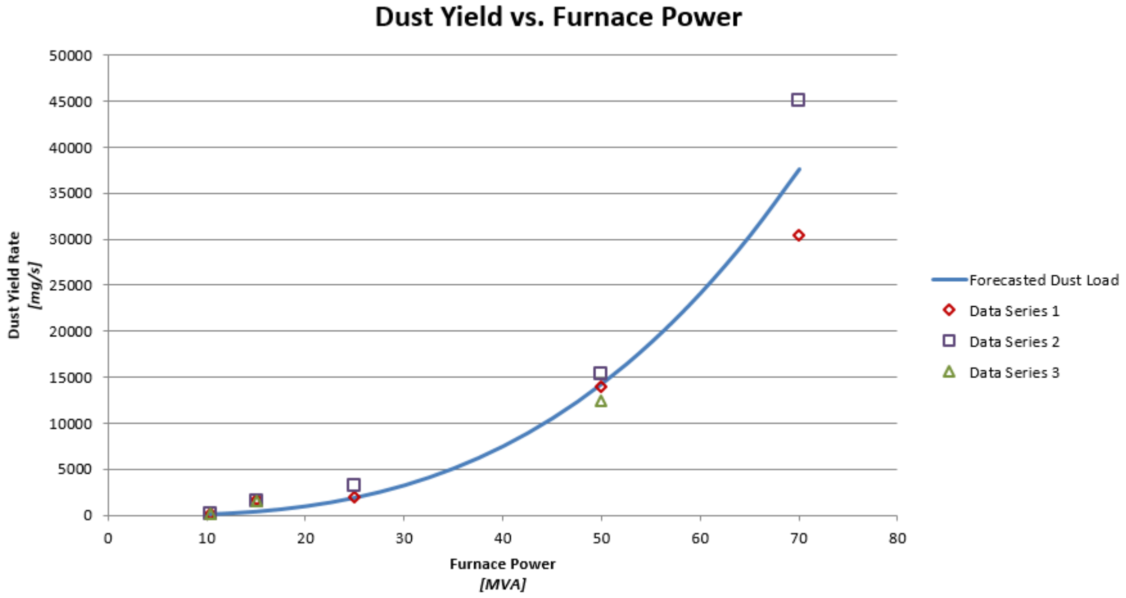


Figure 5-8: Dust yield rate versus furnace power input

Both constants in the equation are determined by the curve-fitting tool in Matlab. The total cross-sectional area of the electrodes is governed by the furnace design, and is used in the equation as it is the energy source over a surface that initiates the smelting process (Benilov, 2007).

5.2.5 Conclusion

All the pre-design experiments that were conducted returned results that were used to determine conclusive trends and a reliable basis for the design to be initiated. When considering both environmental and financial implications as a result of non-compliance, it is critical that the scrubber system can operate at the required efficiency during conditions that cannot be forecasted. Therefore the values used in the design phase are all based on the mean values during testing, however the system must be designed to withstand operational peaks for short periods of time.

6 Scrubber Selection

For the purpose of this study a table is used to score each scrubber system based on its capability to scrub the gaseous mixture and particulate in section 5. This table can be applied to many similar situations provided the scoring is unbiased and only the relevant topics are evaluated. The table can be amended and altered as needed; influencing factors can be changed, as well as the quantity of solutions that will be considered in the evaluation.

Each scrubber solution will be scored from 0 to 10, the latter being the best solution. To eliminate complexity no half-points will be awarded, as this is solely a guideline as to the approach of a suitable scrubber selection. The total for this specific application will be a score out of 100, however different applications call for different requirements, therefore each selection is unique and should be treated as such.

Table 6-1: Evaluation of possible scrubber solutions

Description	**Scrubber Type**				
	Venturi Scrubber	Packed Tower	Fluidized Bed Scrubber	Fabric Filter	ESP
Capability for high temperature	9	3	8	3	6
Capability for flammable gases	9	9	7	7	1
Capability for high dust loads	8	5	8	9	9
Capability for dynamic operation	9	7	4	7	4
Sub-micron particulate collection	9	1	1	9	7
Overall collection efficiency	9	6	6	9	7
Capital outlay cost	3	8	7	3	4
Operating and maintenance costs	4	7	7	8	9
Footprint	8	9	9	3	3
Services requirements	3	7	4	7	7
Total *(x / 100)*	**71**	**62**	**61**	**65**	**57**

It is clear from the information in table 6-1 that a venturi scrubber is the best suited solution for the ferromanganese furnace in this study. The fabric filter is also a solution to be considered, trailing slightly behind, however the capability for high temperature gases prevent it from being used as a singular solution. For a fabric filter to be implemented successfully the gas needs to be quenched upstream, however the use of water can have a negative effect on the fabric bags. Therefore a dry cooler such as a forced-draft cooler needs to be incorporated to reduce the gas temperature. Dry coolers demand high power input as well as

Fabric filters and ESPs require a large area for erection, as their collection efficiency is inversely proportional to the velocity of the gas. To ensure that the gas moves as slowly as possible, the cross-sectional area of the plant needs to be relatively large, increasing the overall footprint.

When considering a wet venturi scrubber it is important to understand the service requirements for the cleaning of the gas. Process water is recycled in the scrubber plant, as it becomes contaminated when exposed to the furnace off-gas. The outlet water from the scrubber plant is pumped to a settling dam

7 Scrubber Design

7.1 Scrubber System

A schematic diagram is always necessary when considering a system so that the properties of each component can be designed accordingly. Once each component has been design the system needs to be considered as a whole. Figure 7-1 indicates each component in the scrubber system and table 7-1 provides a brief description of each component with its corresponding number, each of which will be discussed in detail in this section.

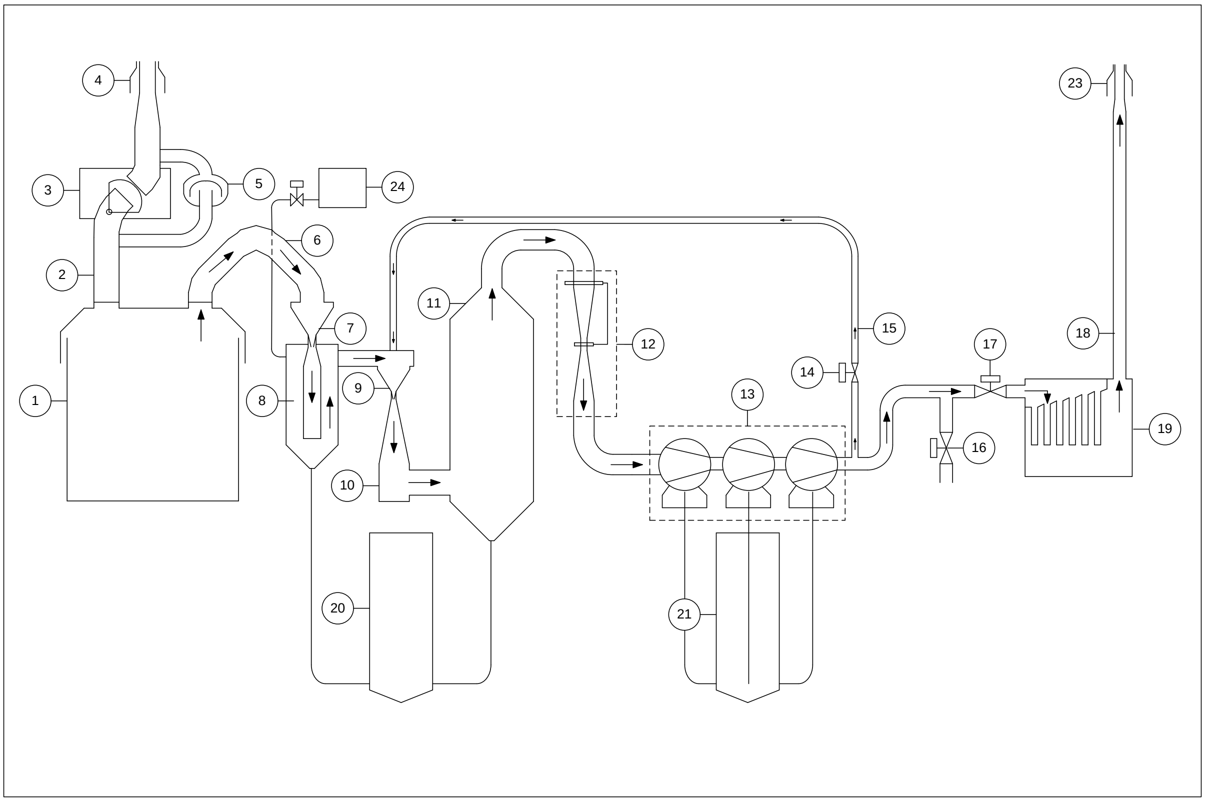


Figure 7-1: Layout of scrubber system components

Table 7-1: Scrubber components

Scrubber Components			
1	Electric arc furnace	13	Main fan train
2	Emergency raw off-gas stack	14	Furnace pressure control damper
3	Emergency stack rotary water seal	15	Recirculation ducting
4	Raw gas flare	16	Distribution gas shut-off valve
5	Furnace over-pressure relief valve	17	Stack flow control damper
6	Raw off-gas transition duct	18	Clean gas stack
7	Primary venturi	19	Reflux water seal
8	Furnace water seal	20	Primary seal pot
9	High pressure venturi	21	Fan seal pot
10	Flooded elbow	22	Clean gas flare tip
11	Cyclonic separator	23	Emergency water tank
12	Differential pressure flow meter		

7.2 Components in a Scrubber System

7.2.1 Electric Arc Furnace

At the start of the process, the electric arc furnace is the initial consideration when design the scrubber plant. All the relevant information regarding the process that takes place within the furnace has been discussed in Section 4.3.

There are, however, two addition aspects that need to be accounted for when considering the ferromanganese smelting process, namely furnace over pressure and eruptions.

7.2.1.1 Furnace over pressure

This is a steady, but significant, positive increase of pressure within the furnace shell. It occurs as a result of the ever changing dynamic reactions which take place during the smelting process. Figure 4-5 clearly indicates the relationship between the CO yield and coke added. If a coagulation of coke was to reduce a small quantity of manganese ore, it would result in an excess of CO gas.

Other mechanisms can also contribute to an excess of off-gas, especially when electrolysis of water takes place, releasing large amounts of oxygen and hydrogen. The high internal furnace temperature causes these gases to combust, also contributing to an increase in pressure. Water can exist from the following sources:

- Equipment in and around the furnace, such as
    - Electrode cooling water leakages
    - Overflow of the emergency stack rotary water seal
    - Water cooled transition duct leakages
- Inherent moisture in the reductant and ore
- Moisture in the carbon paste used in the electrodes

7.2.1.2 Furnace Eruptions

Eruptions seldom occur, but are critical when designing safety features for the longevity of the plant. During the smelting process, the less dense materials move upward in molten state. The lighter materials are part of the slag, and are by-products of the process. The charged material in a ferromanganese reduction process is at ambient temperature when the furnace is charged. There is a significant temperature difference between the molten bed and the charged material, as indicated in Figure 4-4, which can be as much as 1220°C.

The slag moves upward and further away from the electrode tip, which is the thermal source, and starts to cool drastically. The slag then forms a crust between the hot molten bed and the cold charged material due to the large temperature difference. The crust is capable of supporting a significant mass, and therefore prevents the cold charge from moving downward; the void between the molten bed and the crust increases. When the crust is no longer capable of supporting the mass, it collapses, forcing the gas in the void upward with great force. The instantaneous pressure increase causes in a large positive pressure underneath the furnace roof; the large area results in a massive upward force, conforming to Pascal's law.

These eruptions are capable of displacing the furnace roof from its supports entirely, damaging nearby equipment and putting a stop to production. Safety precautions need to be designed in the form of a relief valve, which will be discussed in this section. The cost of repairs is enormous, exceeded only by loss in production revenue.

7.2.2 Emergency Raw Off-Gas Stack

In the event of a system failure within the plant the emergency stack is used to relieve the furnace from over pressurizing. The emergency stack is controlled by a rotary water sealing damper, which is opened when triggered by an operator.

The scrubber system is designed for a specific operating condition of the furnace. When the furnace operates outside of the range of the scrubber, other components such as the emergency stack are enforced to ensure a safe operating environment. During the start-up and shut-down of the furnace, a small quantity of gas is yielded which is less than the scrubber plant requires for stable operation.

During these low gas volume conditions, the emergency stack is opened and the scrubber plant is sealed off to allow the furnace gas to be flared into the atmosphere. There are, however, strict regulations regarding flaring to atmosphere, which include

- Reason for flaring
- Duration of flare
- Furnace power input during flare

It is critical that these aspects are considered by the operating crew, as a furnace might be required to flare to atmosphere at any given time; these procedures must be in place, and the requirements must be adhered to.

7.2.3 Emergency Stack Rotary Water Seal

The rotary water seal is a high-temperature steel plate in the form of an arc which creates a seal in a water bath to isolate the emergency stack. This water bath creates a perfect seal between the arc and the duct inlet when closed. The head of water does not need to be significant, as the results from the furnace pressure testing indicated a maximum pressure of 6.2mm.

To open the seal, the shaft needs to be turned 90° to break the seal and allow gas to pass through. This arrangement allows for the plate to be retracted completely so that there are no obstructions in the gas stream.

Another advantage of this seal arrangement is that the water can be continuously recycled, by adding cold water at the bottom of the seal, and the hot water overflowing in a weir. The movement of water induces cooling of the steel material, and also prevents settling of particulate in the bottom of the water bath.

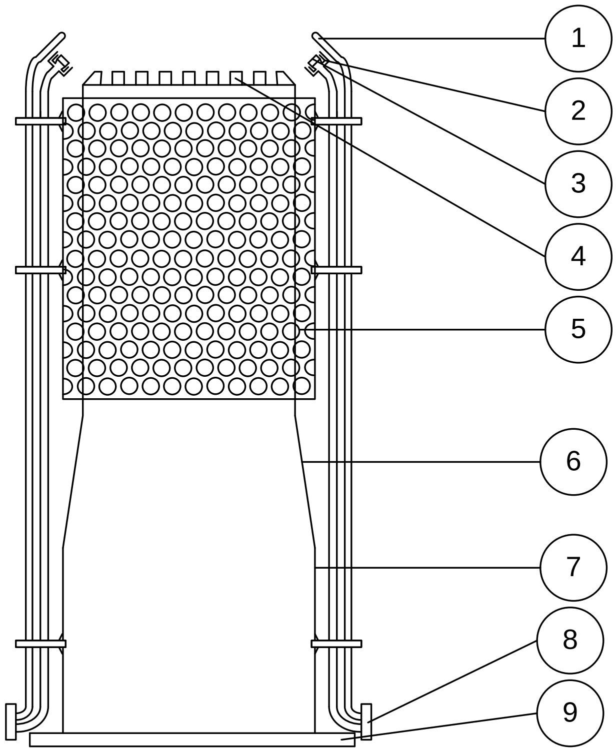
7.2.4 Raw Gas Flare

Legislation requires any flammable gas flared to atmosphere to be combusted. This is to ensure that a cloud does not form above the plant, which could spontaneously combust. Also, CO can have adverse health effects on people when inhaled, however this risk is eliminated when it is combusted, changing it into CO_2 gas. To combust this gas a high temperature flare igniter is used.

Figure 7-2 represents the components in a flare ignition system. When the gas enters the base reduction in the flare diameter it is accelerated, increasing the exit velocity and thus forcing the base of the flame farther from the tip. This ensures that the construction material remains relatively cool and protection of the instrumentation. The tip is fitted with a serrated arrangement to induce a pressure differential between the high velocity gas and the static, higher pressure air. The air is then drawn towards the gas stream and mixes above the tip, allowing ignition to take place.

There are a set of igniters on either side of the flare, which each comprise of an LPG supply, high-energy igniter and a thermocouple. The high-energy igniter is essentially a high voltage spark-plug, which ignites the LPG projected through a nozzle. The igniter will continue sparking until the thermocouple measures a significant temperature, confirming that combustion has started. The LPG and power supply to the flare are then shut off, as it is a waste if they are used permanently.

The perforated cylinder around the flare is to eliminate the drag force of high speed winds. Typically a flare can be as high as 60m in the air, which results in a massive moment on the supports at the base support. The perforation induces a turbulent layer along the cylinder, reducing the pressure drop across the cross-section area of the cylinder, thus reducing the applied force.



Components

1 – Thermocouple
2 – LPG outlet
3 – High energy igniter
4 – Serrated tips
5 – Perforated cylinder shell
6 – Duct reducer
7 – Duct
8 – Terminal connector
9 – Connection flange

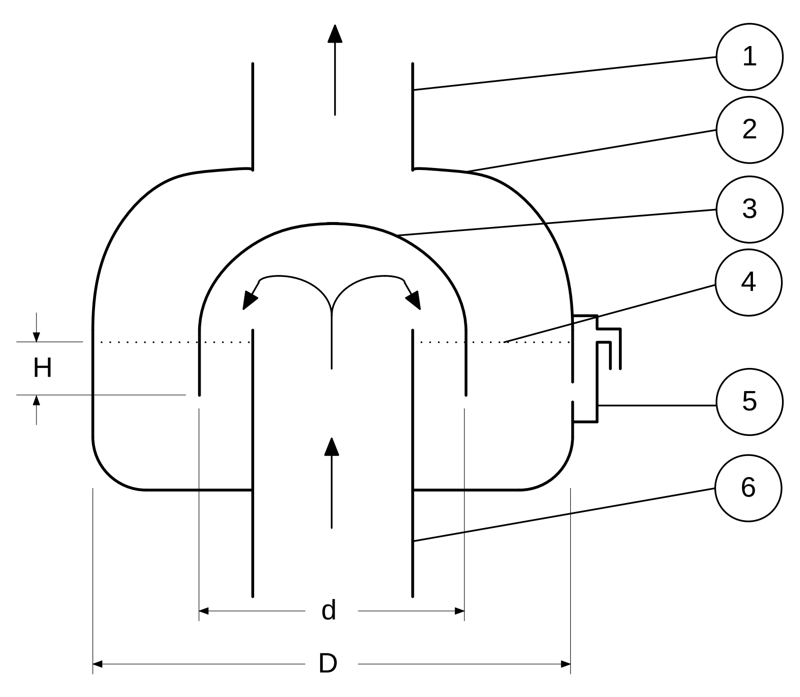
Figure 7-2: Schematic of a flare tip ignition system

7.2.5 Furnace Over-Pressure Relief Valve

Over pressure, as discussed earlier, needs to be accounted for when designing safety features to protect the plant. This component is designed specifically to relief the furnace from eruptions, which demand a robust and fail-proof concept.

The relief valve is essentially a pressure vessel with an interior mushroom-shaped plate. The vessel is filled with water and the plate forms a water seal. In the event of over pressure the water between the mushroom and the inlet duct is displaced downwards, allowing gas to escape through to the emergency stack. The pressure relief valve is always located next to the rotary water seal so that it can be bypassed if necessary. A typical pressure relief valve design is indicated in Figure 7-3.

It is important to note that the hydraulic effect takes place in the water when displaced. The area between the inlet duct and the mushroom must be significantly smaller than the area between the mushroom and the vessel shell. This will ensure that relief pressure is not significantly increased when the water is displaced. If the gas pressure in the duct is less than the water head in the relief valve, nothing will be bypassed which can cause a rupture at a weak point in one of the other components.



Components

1 – Outlet duct
2 – Relief valve shell
3 – Mushroom seal
4 – Water level
5 – Weir
6 – Inlet duct

H – Water head
D – Outer diameter
d – Inner diameter

Figure 7-3: Schematic of a furnace pressure relief bypass valve

7.2.6 Raw Off-Gas Transition Duct

The transition duct connects the furnace to the quench venturi, so as to transport the gas safely to the scrubber plant. Due to high raw gas temperatures transitions duct needs to be design to withstand both a high continuous operating temperature, as well as cater for possible eruptions and temperature spikes. The ideal solution for this is a water cooled duct, which makes use of cooling water within a jacket around the duct to continuously cool the duct temperature. A typical water cooled duct is illustrated in Figure 7-4. The cold water inlet must always be lower than the outlet, so that any steam that might have formed can escape. The water is generally under a high pressure, so that the boiling point is increased.

There are, however, certain parameters that need to be monitored with this sort of equipment. The shell temperature must never decrease below the dew point of the gas; this will prevent acidic build-up on the duct wall, as well as induce scaling within the duct. It is critical to ensure that a proper mass and energy balance is conducted when executing the design, as in equation 6-1 where $\dot{m}_{water}$ needs to be solved.

$$\dot{m}_{water} Cp_{water} (T_{in} - T_{out}) = \dot{m}_{gas} Cp_{gas} (T_{in} - T_{out}) \tag{7-1}$$

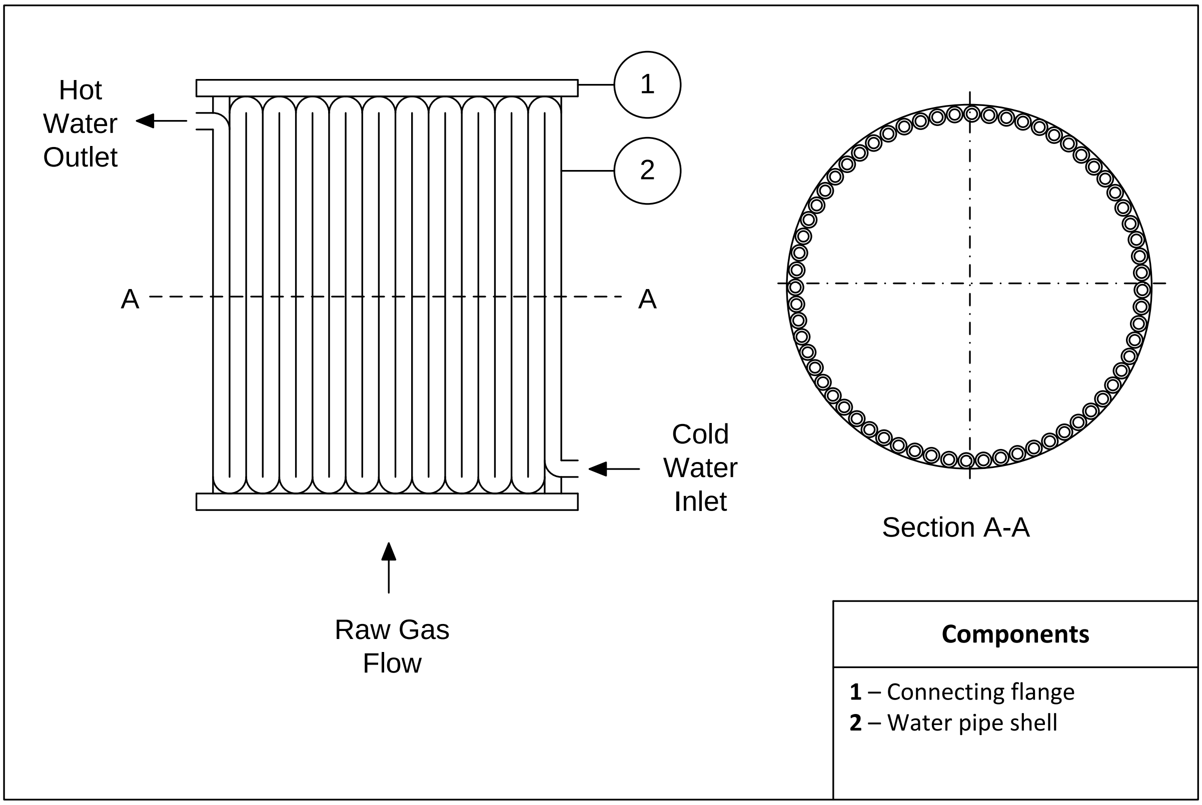


Figure 7-4: Schematic of a raw off-gas transition duct section

7.2.7 Primary Venturi

The first step in handling the gas stream in the scrubber plant is to cool it sufficiently to within equipment capability. Hot gas is more expensive to handle, as it requires higher grade material, and the volumetric flow rate of the gas is greater, demanding larger equipment.

The primary venturi, or quencher, makes use of liquid vapourisation to cool the gas stream. Additional advantages include precipitation of gaseous volatiles and the eliminating a fraction of the particulate matter. Generally, industrial evaporative cooler design is based on steam tables, however they are rarely used for processes other that air (Spellman and Whiting, 2005). For this process, air is not present in the gas stream, therefore the calculations need to be based on psychrometric principals.

Psychrometric charts are generated through experimentation by many different organisations, however they are primarily researched for the HVAC industry, which is air based and below 50°C at atmospheric pressure dependent on elevation. The CO rich gas stream in the ferromanganese reduction process requires a specialised psychrometric chart, which in calculated in this section.

7.2.7.1 Psychrometrics

Pyschrometry is defined as the thermal and physical properties of gas-vapour mixtures (World Meteorological Organisation, 2008). These properties are dependent on a range of factors, which requires certain assumptions to be made before initiating the calculations.

The first step in determining the psychrometric properties of the gas, in to identify the liquid that will be used to quench the stream. As discussed during the previous section, water will be used as the scrubbing liquid, however other processes may require neutralisation of acidic or alkaline gas streams; the applicable scrubbing liquid will then be evaluated in the same manner. Thereafter a Grosvenor chart needs to be generated, which is a plot of temperature versus humidity ratio. The purpose of calculating these values is to determine the mass of water that needs to be added to specific mass of gas for the required cooling to take place.

Firstly, the Antoine equation, derived from the Clausius-Clapeyron equation, is used to determine the vapour pressure of the liquid in equation 7-3 (Antoine, 1888). The Antoine coefficients A, B and C are 5.11564, 1687.537 and 230.17 respectively, and are empirical values. The vapour pressure is measure in mmHg.

$$\log_{10}(P_{vap}) = A - \frac{B}{(T + C - 273.15)} \tag{7-3}$$

Rearranging this equation returns the temperature for a known vapour pressure.

$$T = \frac{B}{A - \log_{10}(P_{vap})} - C + 273.15 \tag{7-4}$$

The total pressure is described in equation 7-5.

$$P_{tot} = P_{atm} + P_{gas} \tag{7-5}$$

Additional equations need to be solved to determine a basis for the cooling relationship. The partial vapour pressure needs to be determined, as indicated in equation 7-6. The molecular mass of the gas used in the equation is the average sampled in the previous section.

$$P_{vap_{par}} = P_{tot}\left(m_l \cdot \frac{MM_l}{MM_g + MM_l}\right)\left(\frac{1}{g \cdot SG_{HG}}\right) \tag{7-6}$$

Equation 7-5 is then substituted into equation 7-6 to determine the temperature for a specific humidity ratio.

$$T = \frac{B}{A - \log_{10}\left[P_{tot}\left(m_l \cdot \frac{MM_l}{MM_g + MM_l}\right)\left(\frac{1}{g \cdot SG_{HG}}\right)\right]} - C \qquad (7\text{-}7)$$

To generate an accurate plot, the relative humidity (RH) should be calculated for a range of input values. RH can be defined as the ratio of partial vapour pressure to equilibrium vapour pressure (Perry, 1998), indicated in equation 7-8.

$$\emptyset = \frac{e_l}{e_l^*} \times 100\% \qquad (7\text{-}8)$$

The humidity ratio is defined in equation 7-9.

$$W = \frac{m_l}{m_g} \qquad (7\text{-}9)$$

The relevant data to be calculated for the Grosvenor plot is indicated in table 7-2. The temperature and humidity ratio are not single values. Temperature is a function of humidity ratio for a specified RH.

Table 7-2: Temperature and humidity ratio to be calculated

Relative Humidity	Temperature	Humidity Ratio
100 %	* (to be calculated)	*
80.0 %	*	*
60.0 %	*	*
40.0 %	*	*
20.0 %	*	*
10.0 %	*	*
5.00 %	*	*
2.50 %	*	*
1.00 %	*	*
0.10 %	*	*

Example calculation:

Assumptions: m_l = 0.1 kg; RH = 100%

$$P_{tot} = P_{atm} + P_{gas}$$

$$P_{tot} = 84.5 + 0.01 \qquad = 84.51\ kPa$$

$$T = \frac{B}{A - \log_{10}\left[P_{tot}\left(m_l \cdot \frac{MM_l}{MM_g + MM_l}\right)\left(\frac{1}{g \cdot SG_{HG}}\right)\right]} - C$$

$$T = \frac{1687.537}{5.11564 - \log_{10}\left[84.51\left(0.1 \cdot \frac{18.02}{27.46 + 18.02}\right)\left(\frac{1}{9.81 \cdot 13.59}\right)\right]} - 230.17 \qquad = 21.11\ ℃$$

Once the series of values is determined for each RH value, the data can be plotted, with humidity ratio on the *y*-axis and temperature on the *x*-axis. RH of 100% is the equivalent of the liquid's dew point and is the maximum vapour capacity of a specific volume of gas; additional vapour will condense and form precipitation. The RH values plotted are indicated in Figure 7-4.

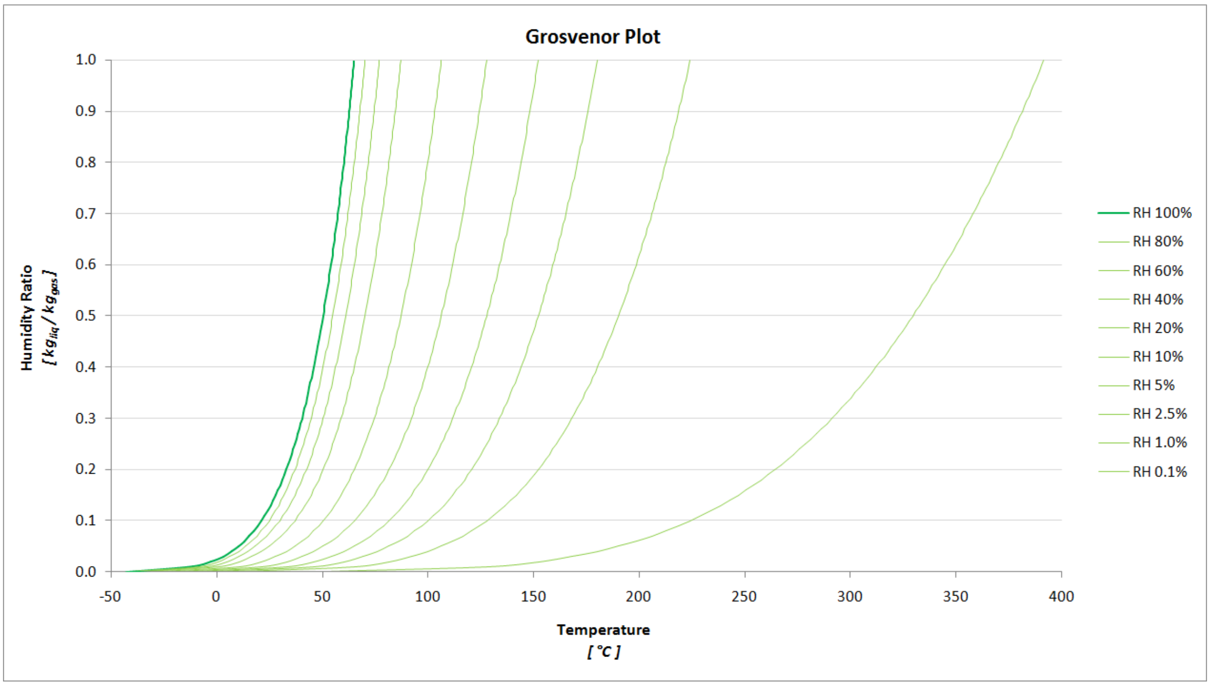


Figure 7-5: Grosvenor plot for the required relative humidity values of water

7.2.7.2 Adiabatic Saturation

An adiabatic process can be defined as a process that takes place without the transfer of external heat or matter (Caratheodory, 1909). Adiabatic saturation can therefore be described as the saturation that takes place in a process without external heat transfer. The process occurring in this instance is the exchange of energy between the hot gas and the water which is vapourized. When matter undergoes a phase transition, latent heat is absorbed by the matter or the system (Pierre, 1998). An empirical formula was derived through experiments by Rogers and Yau (1989) to determine the latent heat of water as a function of temperature, indicated in equation (6-10), where temperature is T and the formula is accurate for a water temperature range of -20°C to 40°C, in *kJ/kg*.

$$L_{water}(T) = 2500.8 - 2.36T + 0.0016T^2 - 0.00006T^3 \tag{7-10}$$

The water used in the scrubber plant is supplied by a settling dam, which is subject to atmospheric temperature change. Water temperatures may vary significantly due to seasonal change, however an average of 22.5°C was measured and will be used for the calculations in this study.

To determine the amount of energy transferred between the water and the gas during vapourization, an energy balance needs to be equated. Equation 7-11 indicates the enthalpy for the gas for a specific heat capacity in *kJ/kg*.

$$h_{gas} = C_P \Delta T \tag{7-11}$$

Substituting these two equations and rearranging the variables, equation 7-12 can be declared and returns a result in *kJ*.

$$h_{gas,f} = m_{gas} \cdot h_{gas,i} - m_{water} \cdot L_{water} \tag{7-12}$$

Substituting equation 7-12 with equation 7-11 allows the temperature difference that occurred to be determined.

$$\Delta T_{gas} = \frac{m_{water} \cdot L_{water}}{m_{gas} \cdot C_{P,gas} + m_{water} \cdot C_{P,water}} \tag{7-13}$$

Once the temperature difference has been determined for a specific mass of water m_{water} it can be subtracted from the initial gas temperature. This returns the final temperature for a finite value of water, however the accuracy of the solution increases as m_{water} approaches zero. Equation 7-13 also needs to be expanded as all the variables are dependent on the temperature of the thermodynamic system at any given instance. Equation 7-14 returns the specific heat capacity of gas and liquid as a function of temperature, where variables a_0 through a_4 are empirical values determined by Poling *et al* (2001) and are indicated in table 7-3.

$$\frac{C_P^0}{R} = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 \tag{7-14}$$

Table 7-3: Specific heat coefficients and capacities at STP (adapted from Poling et al., 2001)

Specific Heat Capacities						
Description	a_0	a_1 $[x10^{-3}]$	a_2 $[x10^{-5}]$	a_3 $[x10^{-8}]$	a_4 $[x10^{-11}]$	C_P/R @ 298.15 K [kJ/kg-K]
Carbon Monoxide	3.912	-3.913	1.182	-1.302	0.515	29.14
Carbon Dioxide	3.259	1.356	1.502	-2.374	1.056	37.13
Hydrogen	2.883	3.681	-0.772	0.692	-0.213	28.84
Oxygen	3.630	-1.794	0.658	-0.601	0.179	29.38
Nitrogen	3.539	-0.261	0.007	0.157	-0.099	29.12
Methane	4.568	-8.975	3.631	-3.407	1.091	35.69
Water	4.395	-4.186	1.405	-1.564	0.632	75.29

The specific heat capacity of an object is the ratio between the heat added and the resultant temperature (Halliday et al., 2013). Water has three main different heat capacity values, dependent on its phase, indicated in Figure 7-6.

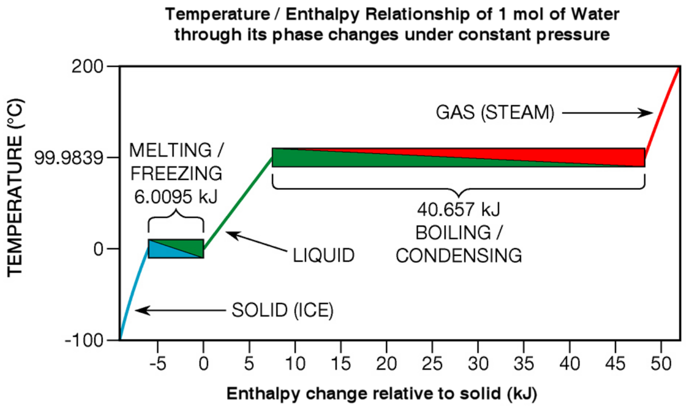


Figure 7-6: Enthalpy of water at different phases

There are, however, limitations to equation 7-14, as the heat capacity of water changes below its boiling point. Also, complete water vaporization does not occur below boiling point, as is it undergoes a gas-vapour mixture, i.e. the quality predicts how much gas is capable of vapourizing the water. Therefore, the more saturated the gas becomes below boiling point, the more difficult it is for vapourization to occur.

The limitations of the water can be defined in equations 7-15 and 7-16.

For T_{gas} >99.98

$$C_P = \left(\frac{1}{MM}\right)(a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4) \tag{7-15}$$

For T_{gas} ≤99.98

$$C_P = \left(\frac{1}{\bar{R}}\right)(a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4) \tag{7-16}$$

Example calculation:

Assumptions: m_g = 1 kg; ml = 0.0005 kg; $T_{g,i}$ = 250°C; T_w = 22.5°C, W_i = 0

$$L_{water}(T) = 2500.8 - 2.36T + 0.0016T^2 - 0.00006T^3$$

$$L_{water}(T) = 2500.8 - 2.36(22.5) + 0.0016(22.5)^2 - 0.00006(22.5)^3 \quad = \quad 2447.8\ kJ/kg$$

$$C_{P,gas} = v_{CO}\cdot C_{P,CO} + v_{CO_2}\cdot C_{P,CO_2} + v_{H_2}\cdot C_{P,H_2} + v_{O_2}\cdot C_{P,O_2} + v_{N_2}\cdot C_{P,N_2} + v_{CH_4}\cdot C_{P,CH_4} \quad = \quad 2.31\ kJ/kg\text{-}K$$

$$C_{P,water} = \left(\frac{1}{\bar{R}}\right)(a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4) \quad = \quad 1.86\ kJ/kg\text{-}K$$

$$T_{f,gas} = T_{i,gas} - \frac{m_{water}\cdot L_{water}}{C_{P,gas}}$$

$$T_{gas} = 250 - \frac{(0.0005 \times 2447.8)}{2.31} \quad = \quad 249.47\ ℃$$

The assumptions in the calculation are that the gas is dry, i.e. there is no C_P value for inherent water in the gas. Therefore the latent water energy is only divided by the heat capacity of the gas, however this changes when gas in vapourized, as the water mass within the gas increases as the gas cools, altering the resultant heat capacity.

These equation need to be applied to the gas stream for each finitely small addition of water. The resultant equation is thus the initial temperature less the sum of all the temperature differences, which must be solved numerically, where X_l is the water quality in a gas-vapour mixture and only applies when $T < T_{boiling}$.

$$T_{sat} = T - \sum_{i=1}^{T_{sat}=RH100} \frac{\delta \cdot L_{water}}{m_{gas} \cdot C_{P(i-1),gas} + m_{water} \cdot C_{P(i-1),water}} \left(\frac{1}{1 - X_l}\right) \qquad (7\text{-}17)$$

Adiabatic saturation lines can be plotted over the Grosvenor plot in Figure 7-4 at different initial temperatures. For the purpose of this study, 200°C, 800°C and 1 100°C were used to plot three adiabatic saturation lines for, indicated in Figure 7-7. The change in the vapourization efficiency of water is clearly visible below the boiling temperature.

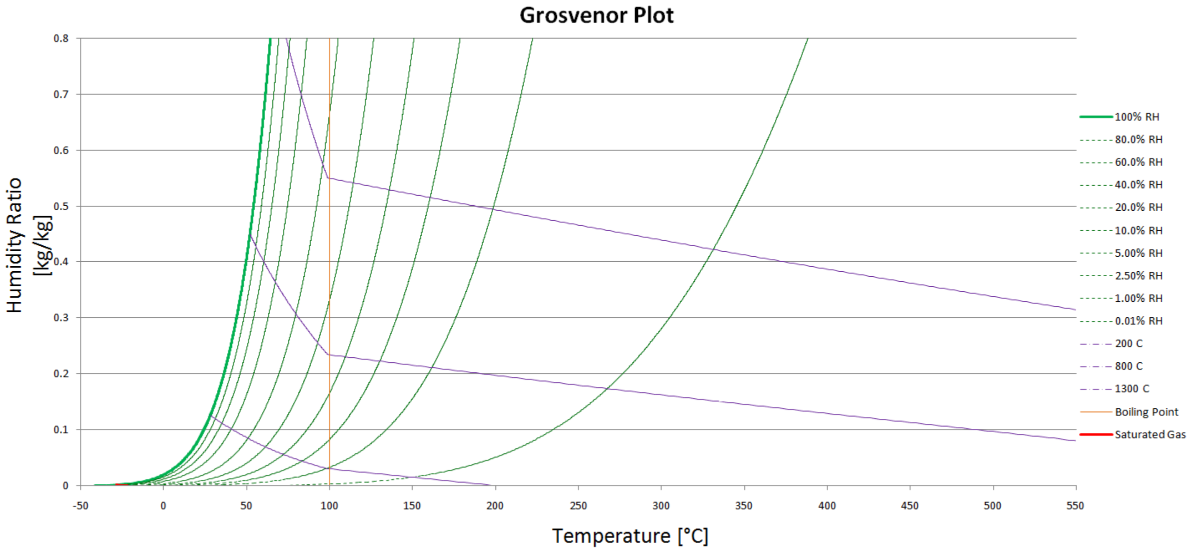


Figure 7-7: Grosvenor plot including adiabatic saturation lines

7.2.7.3 *Applied Adiabatic Saturation*

For the design of the scrubber in this study, the average gas temperature in the furnace will be used as an operating condition, and both the minimum and maximum temperatures will be evaluated to determine whether the psychrometric method is capable of quenching the gas.

When substituting the range of gas temperatures in table 5-2 into equation 7-17, a saturated gas temperature for each initial gas temperature in returned in table 7-4. These values will then be compared with the final experimentation to determine the accuracy of the design.

Table 7-4: Initial gas temperature vs. saturated gas temperature

Gas Temperatures			
Description	Initial Temperature *[℃]*	Saturated Temperature *[℃]*	Liquid Added *[kg/kg]*
Average	310.50	41.38	0.26
Maximum	497.90	49.61	0.40
Minimum	244.00	37.34	0.21

7.2.7.4 Component Design

The primary venturi is a component that must be designed to withstand both high temperatures, and a large volumetric gas flow rate. The actual flow rate of the gas increases with temperature (Clapeyron, 1834), thus the volumetric flow rates of the gas before and after the primary venturi need to be calculated for sizing of the inlet and outlet. If the gas velocity is too low, particulate will drop out of the gas stream in the connecting ducting, causing build-up and unnecessary maintenance demands. If the gas velocity is too high, the dynamic pressure in the system increases significantly, demanding higher power input and increasing the operating costs. Figure 7-8 indicates a typical layout for a primary venturi.

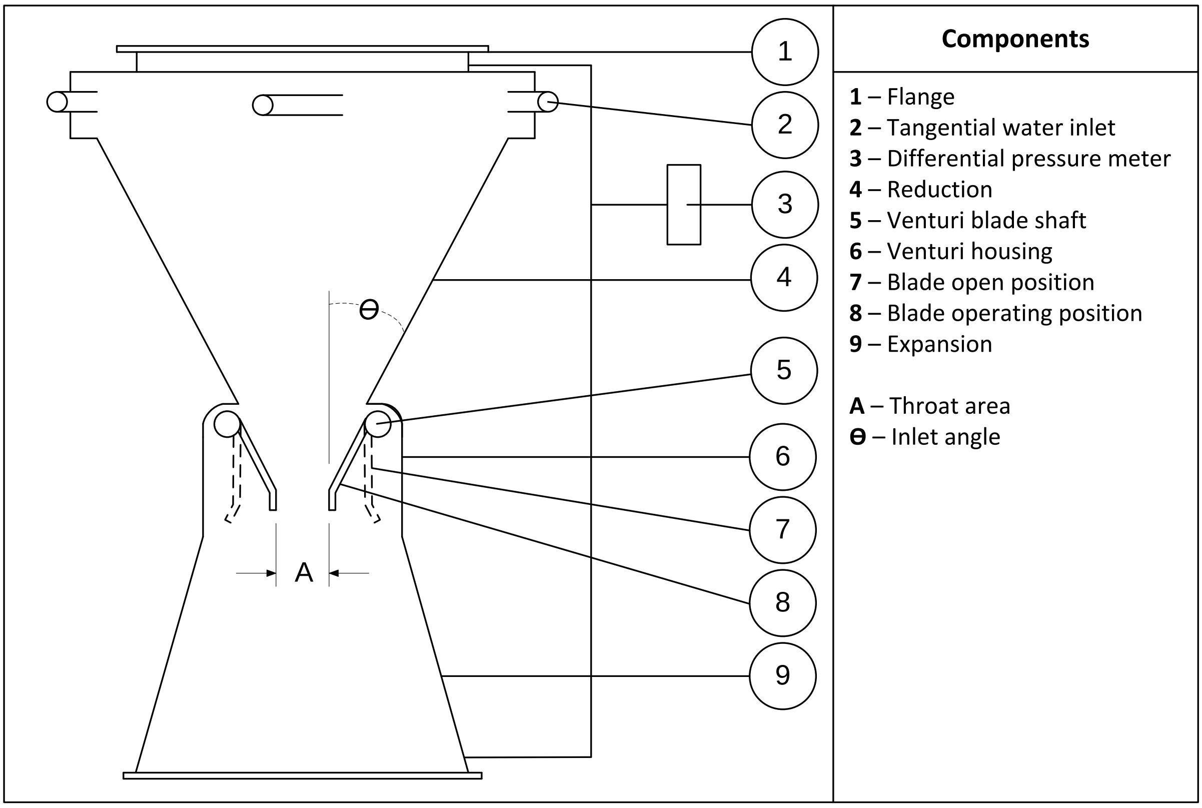


Figure 7-8: Schematic of the primary venturi

To determine the gas volume before and after the primary venturi, the gas density needs to be calculated and then the ideal gas law needs to be applied, indicated in equation 1-1. To determine the gas density, equation 7-18 is applied.

$$\rho = \frac{P\,MM_g}{R\,T} \tag{7-18}$$

Table 7-5: Ratio between the inlet and outlet gas volumetric flow rate

Gas Flow Rate						
Description	Volume	Flow *[Nm³/s]*	T=310.50°C		T=35.78°C	
			Density *[kg/m³]*	Flow *[Am³/s]*	Density *[kg/m³]*	Flow *[Am³/s]*
Carbon Monoxide	61.24 %	2.690	0.5978	5.749	1.129	3.043
Carbon Dioxide	12.74 %	0.559	0.9392	1.196	1.774	0.633
Hydrogen	9.77 %	0.429	0.0430	0.917	0.081	0.485
Oxygen	1.10 %	0.043	0.6829	0.103	1.290	0.054
Nitrogen	14.4 %	0.632	0.5979	1.352	1.129	0.715
Methane	0.71 %	0.003	0.3424	0.066	0.646	0.035
Total	**100 %**	**4.392**		**9.384**		**4.967**

From table 7-5 the ratio between the gas inlet and outlet volumetric flow rate can be defined as $Q_i : Q_o$, which can be applied to the inlet and outlet area to maintain a constant velocity before and after the primary venturi.

Once the flow rate through the primary venturi has been determined, a calculation needs to be done to ensure that the injected liquid is sufficiently vapourized to ensure efficient quenching. Boll et al. (1974) derived an equation for droplet size as a function of relative gas velocity, indicated in equation 7-19.

$$d_{liq} = \frac{4.22e^{-2} + 5.77e^{-3}\left(\frac{1000Q_l}{Q_g}\right)^{1.922}}{v_{rth}^{1.602}} \tag{7-19}$$

This is a complex calculation as the velocity in in the primary venturi throat is unknown, therefore it needs to be solved iteratively with an additional set of equations. To determine the required equations, the thermodynamic properties of liquid needs to be evaluated and then applied to the vapourization process. The liquid droplets are subject to a convective heat transfer in the primary venturi, and therefore equation 7-20 can be utilized, where d_{liq} is the droplet diameter.

$$q = A_{liq} \cdot k \cdot d_{liq} \Delta T \tag{7-20}$$

$$k = \frac{1}{2}\left(k_{liq} + k_{gas}\right) \tag{7-21}$$

For this equation, we can assume that q is equal to the latent vapourization heat of water, k_{gas} is the sum of the weighted thermal conductivity coefficients for the gases present, and ΔT is the temperature difference calculated in table 7-4. Therefore the only variables required are the liquid surface area and the droplet diameter. These are both a function of equation 7-19 as the liquid surface area and the liquid volume are indicated in equations 7-21 and 7-22 respectively.

$$A_{sphere} = \pi d^2 \tag{7-22}$$

$$V_{sphere} = \frac{1}{6}\pi d^2 \tag{7-23}$$

$$N_{droplets} = \frac{Q_{liq}}{V_{sphere}} \tag{7-24}$$

$$Q_{liq} = W * \dot{m_{gas}} \tag{7-25}$$

The pressure drop across a venturi throat is a function of velocity and liquid-to-gas ratio, which is indicated in equation 7-26 (adapted from Hesketh, 1986).

$$\Delta P = \left(\frac{v_{th}^2 \rho_g}{1.879}\right) A_{th}^{0.133} \left[0.56 + \frac{16.6 Q_l}{Q_g} + 40.7\left(\frac{Q_l}{Q_g}\right)^2\right] \tag{7-26}$$

The volume of liquid added to the gas in table 7-4 can be divided by the volume of the droplet in equation 7-22. This will result in the total number of droplets in the gas stream, assuming they are all of equal diameter. Subsequently equation 7-25 can be used to determine total pressure drop across the primary venturi throat. By substituting each of these equations into an iterative calculation, the results returned are indicated in table 7-6.

Table 7-6: Results returned to determine the throat velocity

Variable	Result	Unit
k	0.12773	W/m-K
q	2 447.80	W
ΔT	274.70	℃
A_{liq}	1 400.00	m^2
$N_{droplets}$	3.884×10^{10}	-
A_{sphere}	3.605×10^{-8}	m^2
V_{sphere}	6.43×10^{-13}	m^3
v_{th}	66.50	m/s
d_l	5.106×10^{-5}	m
ΔP	2 248.00	Pa
A_{throat}	0.4377	m^2

As discussed earlier, the collection efficiency in a venturi scrubber is dictated by the pressure drop across the throat. The primary venturi is designed to quench the hot gas stream, however there is a secondary benefit of this equipment. The pressure drop generated for the atomization of the liquid also contributes towards the collection of particles.

7.2.8 Furnace Water Seal

In the event of an emergency, the first priority is to isolate the furnace from the extraction of the primary off-gas scrubber. Due to the high temperature of the off-gas and the safety hazards paired with the escape of carbon monoxide, it is difficult to isolate the furnace with a mechanical shut-off valve or spade. During the movement of a mechanical valve gas can easily escape to atmosphere, or air can be drawn into the gas stream resulting in an explosion.

To account for furnace isolation during certain events a mechanism needs to be implemented that can withstand the immense heat, as well as positively seal the interconnecting duct without the risk of gas escape or ingress. An apt solution is a barometric water seal, which incorporates water within a vessel to obtain a pressure head, as well as maintain a cool surface on the mechanical equipment in the presence of hot gas. A typical arrangement for a water seal is indicated in Figure 7-9.

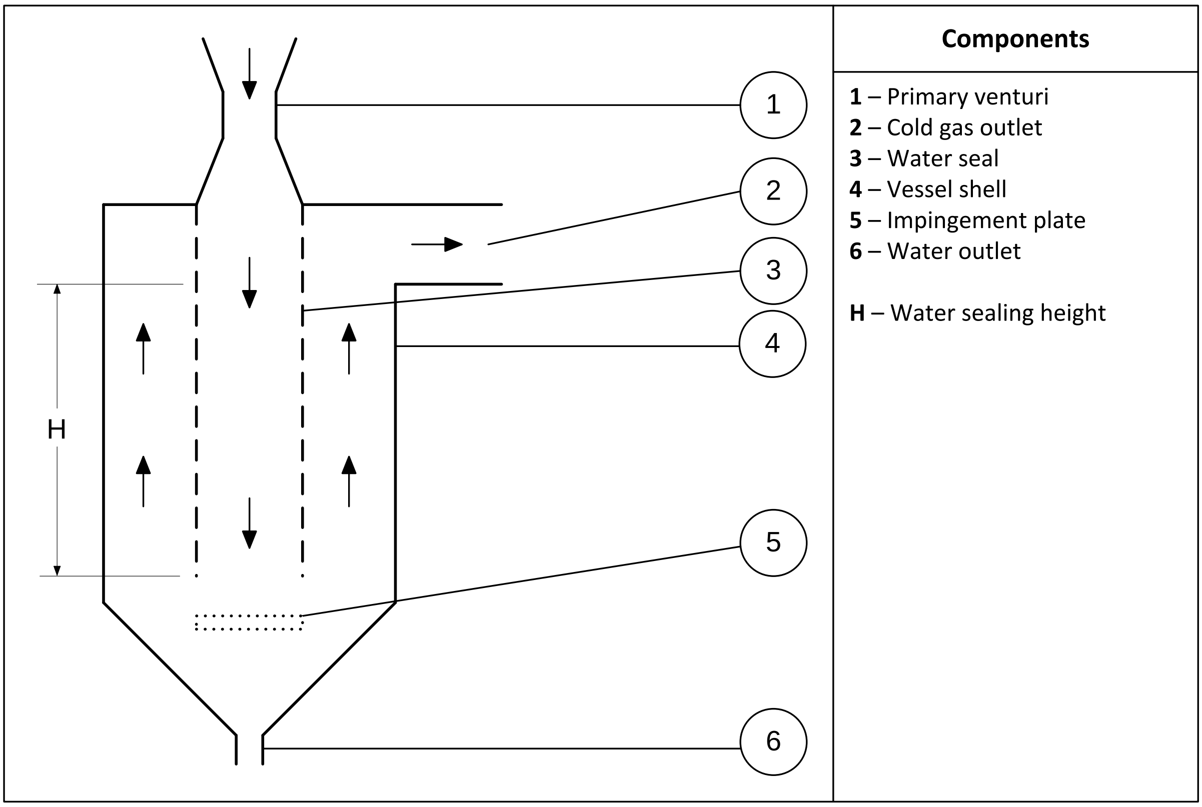


Figure 7-9: Schematic of a furnace water seal

The water seal makes use of a simple sealing mechanism, in which the head of water creates a positive seal greater than the furnace can supply, or that which the scrubber can extract. The equation for this sealing pressure is indicated in equation 7-27, where *H* is in metres.

$$P = \rho_{water}\, g\, H \tag{7-27}$$

The operation of the water seal is simple and near impossible to fail. A spring-loaded isolation valve is located bellow the water outlet at the bottom of the water seal. The valve is fail-closed, meaning that it will use the force of the spring to close if the compressed air or electrical supply were to fail. In addition to the water supply from the primary venturi, a second water supply continuously feeds the water seal at a high flow rate. Once the isolation valves has closed the water level within the vessel will begin to rise until it overflows to the outlet. The difference in height between the bottom of the seal and the outlet duct dictates the sealing pressure capability of the water seal.

The water seal is a dual purpose component, as it serves a purpose for dust collection in addition to the main isolation mechanism. Elimination mechanisms discussed in Section 2 are applied in this piece of equipment, specifically targeting interception and diffusion. This can be described as the phenomena that occurs when a particle has been attached to a liquid droplet, but requires a significant impact to force the particle within the surface of the droplet. To cause this impact an impingement plate is inserted bellow the water seal outlet, directly below the primary venturi.

The inner water seal is significantly narrower and has less sectional area than the outer vessel. This allows the gas to move at a high speed when exiting the primary venturi, but decelerates when moving upward toward the outlet. This upward velocity is based on the force of the moving gas on the droplet as a function of aerodynamic diameter. This allows the droplets which contain particulate to drop out of the gas stream before reaching the outlet. Particulate collection is not the primary goal when designing the primary venturi and water seal, however their properties can be utilized to design more compact and efficient systems.

7.2.9 High Pressure Venturi

By the time the gas reaches the high pressure venturi (HPV) it has been quenched and a large portion of the particulate matter has been removed. It is clear, however, that a large portion of the PSD indicated in Section 5 is smaller than 2 *µm*; these will not be remove efficiently by the primary venturi, hence the implementation of a venturi with a greater pressure drop.

To determine exactly how much particulate needs to be removed, a calculation needs to be done to determine the mass for each PSD range. The HPV is will be designed according to the particulate elimination determined as a function of mass, as legislative rules dictate emission limits in mg/m^3. The results are indicated in table 7-7, and are calculated by multiplying the PSD ranges with the dust load in the gas. This calculation is only conducted for the operating furnace power input of 42 MW.

Table 7-7: Weighted PSD at 42 MW furnace load

Particle Size Distribution					
PSD Range	Percentage	Dust Load *[mg/Nm³]*	Gas Yield *[Nm³/s]*	Dust Yield *[mg/s]*	Weighted *[mg/Nm³]*
< 1 µm	2.60 %	37 775.13	4.393	4 314.59	982.15
1 µm – 2 µm	20.34 %	37 775.13	4.393	33 753.44	7 683.46
2 µm – 5 µm	45.51 %	37 775.13	4.393	75 522.09	17 191.46
5 µm – 10 µm	22.86 %	37 775.13	4.393	37 935.28	8 635.39
> 10 µm	8.68 %	37 775.13	4.393	14 404.16	3 278.88

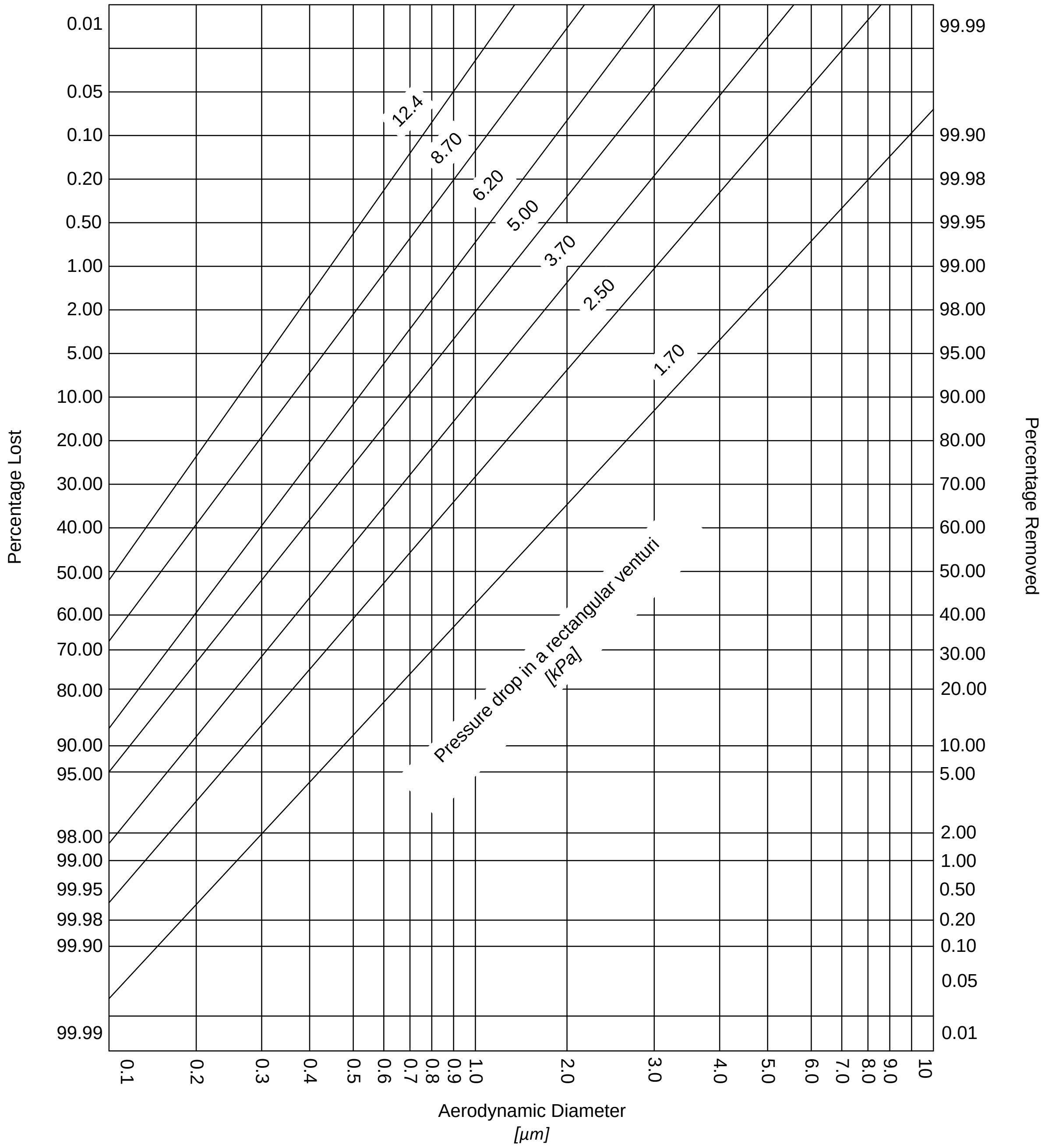


Figure 7-10: Venturi collection efficiency as a function of particle diameter and pressure drop (adapted from Hesketh, 1986)

To design a scrubber plant accurately, the particle size distribution (PSD) needs to be determined. The collection efficiency of a venturi is a function of the PSD, indicated in equation 7-28 and 7-29, where d_p^2 is the particle diameter (Spellman and Whiting, 2005). It is clear from both the equations and Figure 7-10 that the venturi collection efficiency is proportional to the particle's aerodynamic diameter.

$$\eta = 1 - e^{(-kR\sqrt{\psi})} \qquad (7\text{-}28)$$

$$\psi = \frac{d_{aer}^2\, \rho_p\, V_t}{9\, \mu_g\, d_l} \qquad (7\text{-}29)$$

7.2.9.1 *Component Design*

There are many aspects to consider when designing the high pressure venturi, all of which are critical to ensure that the collection efficiency is sufficient for the required mass of particulate to be removed from the gas stream. The HPV has a very similar arrangement to that of the primary venturi, however it is significantly narrower to accelerate the gas to achieve the increase in gas velocity. A typical arrangement of an HPV is indicated in Figure 7-11.

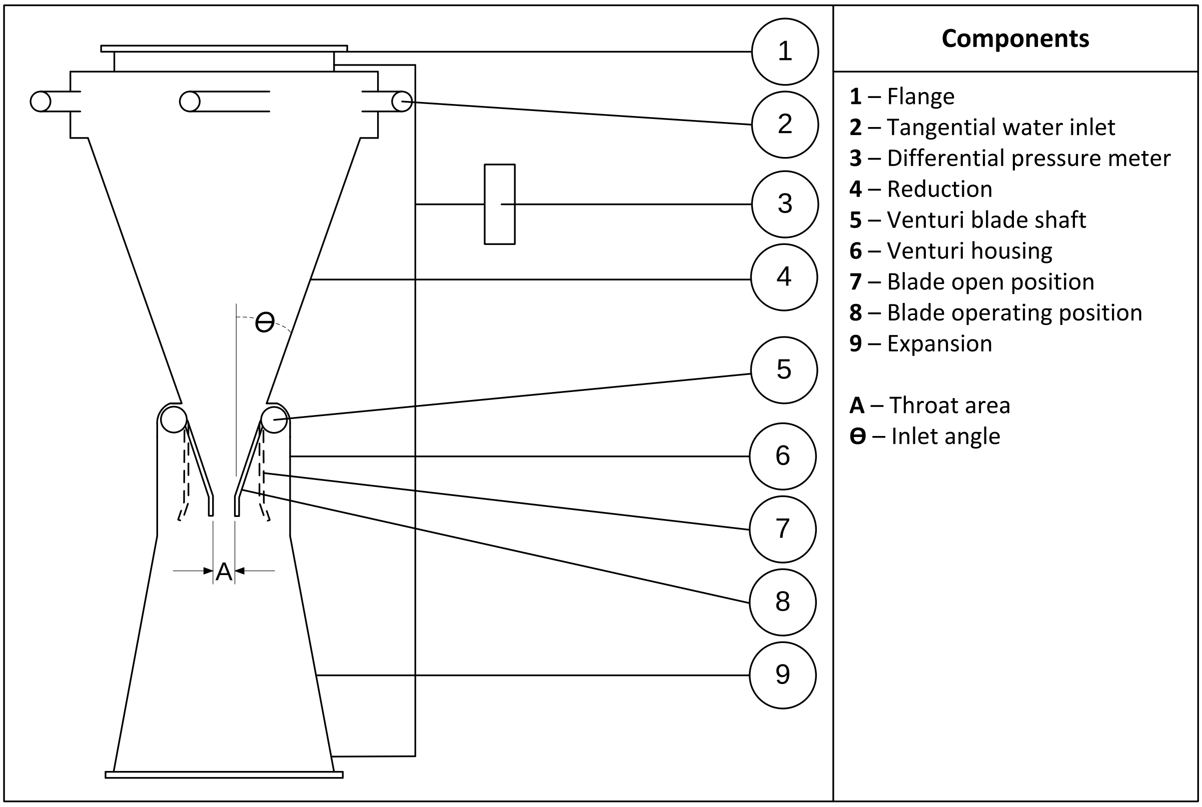


Figure 7-11: Schematic of a high pressure venturi

Legislation dictates that 100 *μm/Nm³* is the maximum allowable emissions for an industrial application. To determine a collection efficiency to achieve this, the allowable rate can be divided by the total dust load, returning a value of 99.735%. This can rather be recalculated to eliminate a required percentage of the submicron particles, assuming a collection efficiency of the larger particles to be 100%. This returns a value of 89.81% for particles smaller than 1 *μm.* This is the efficiency that will be designed for regarding the HPV.

When considering the collection efficiency of a wet venturi scrubber, the Johnstone equation can be used, as indicated in equation 7-30, where K is a geometrical particle constant and ψ is the inertial impaction parameter and is defined in equation 7-31. This equation substitutes the aerodynamic diameter with the actual diameter by decreasing the inertial impaction parameter by a factor of two.

$$\eta = 1 - e^{\left(-K\left(Q_l/Q_g\right)\sqrt{\psi}\right)} \qquad (7\text{-}30)$$

$$\psi = \frac{C\, d_p^2\, \rho_p\, v_t}{18\, \mu_g\, d_l} \tag{7-31}$$

To account for effects on small particles the Cunningham correction factor *C* is applied, which is a derivation of Stokes' law, and indicated in equation 7-32 (Cunningham, 1910).

$$C = 1 + \frac{T(6.21 \times 10^{-4})}{d_p} \tag{7-32}$$

Equation 7-30 can be declared equal to 89.81% where $d_l = 1\ \mu m$; subsequently equation 7-31 can be substituted to find the value for V_t, the throat velocity. These equations are to ne solver iteratively with the properties for the particulate from Section 5. The inertial impaction parameter is a function of particulate density, where the efficiency is proportional to the density, indicated in Figure 7-12 where the series is plotted using the aforementioned equations.

Figure 7-12: Collection efficiency of a wet venturi scrubber vs particulate density

To ensure that the scrubber is designed for the worst possible case, the particulate with the least density will be used, i.e. carbon, which has a density of 1.9 g/cm^3. If there is a smaller mass fraction of carbon in the gas stream the collection efficiency will increase. This assumption is critical, as the dust yield is not fixed and firm; fluctuations are prominent and need to be accounted for in the design to ensure that legislative rules are adhered to.

According to Rudnick et al. (1986) the optimal liquid-to-gas ratio for particulate removal is 0.936 and 1.337 $m^3/1000$. The L/G for study is chosen as 1.337, as it is the maximum value for optimal collection, however the liquid input is greater allowing a thicker film on the internal surfaces of the HPV. This helps to decrease wear on the internal surfaces, prolonging the life of the scrubber.

The variable and equation discussed are applied to determine the design criteria for the HPV. As with the primary venturi it is important to calculate the gas velocity required and subsequently the venturi throat area. These two parameters are critical for a detail design of the component to be done. The results returned from the calculations are indicated in table 7-8.

Table 7-8: Results returned to determine the throat velocity

Variable	Result	Unit
η	0.8981	-
K	0.171	-
d_p	1.0 x10^{-6}	*m*
T_{gas}	308.2	*K*
C	1.191	-
Q_L/Q_G	1.337	-
ρ_{gas}	1.107	kg/m^3
ρ_p	1900.00	kg/m^3
μ_{gas}	1.802 x10^{-5}	*Pa.s*
v_{th}	181.7	*m/s*
d_l	1.271 x10^{-5}	*m*
Δp	18 270.00	*Pa*
A_{throat}	0.0273	m^2

To ensure that the resulting values are suitable for the scrubber, each PSD range needs to be evaluated with the calculated velocity. The collection efficiency for each PSD range is indicated in table 7-9, where v_{th} is equal to 181.7 *m/s*. The primary venturi also contributes towards the total collection efficiency, and needs to be incorporated in the calculations.

Table 7-9: Collection efficiency for each PSD range

	Collection Efficiency			
	PSD Range	Collection Efficiency	Weighted *[mg/Nm³]*	Residual *[mg/Nm³]*
Primary Venturi	*< 1 µm*	52.49 %	982.15	466.61
	1 µm – 2 µm	74.88 %	7 683.46	1 930.08
	2 µm – 5 µm	92.94 %	17 191.46	1213.71
	5 µm – 10 µm	99.84 %	8 635.39	13.81
	> 10 µm	100.0 %	3 278.88	0.00
Total				***3 624.21***
High Pressure Venturi	*< 1 µm*	89.98 %	466.61	47.45
	1 µm – 2 µm	96.44 %	1 930.08	24.12
	2 µm – 5 µm	100.0 %	1213.71	0.00
	5 µm – 10 µm	100.0 %	13.81	0.00
	> 10 µm	100.0 %	0.00	0.00
Grand Total				***71.57***

The resultant emission is allowable for the scrubber plant, as it falls within the average emission rate. The results in table 7-9 are still conservative, as the density used was that of carbon, meaning that the collection efficiency will most definitely be higher in practicality. It is impossible to calculate exactly what the throat velocity needs to be, as the particulate composition per unit of gas fluctuates.

7.2.9.2 Venturi Control

During start-up of the scrubber only a small quantity of gas passes through the system. The venturi therefore needs to be dynamic to change the resistance of the system to prevent a system stall. An actuator is attached to the shaft of the venturi blade, which keeps it in a fully open position until the scrubber has reached an equilibrium and then proceeds to close to its operating position.

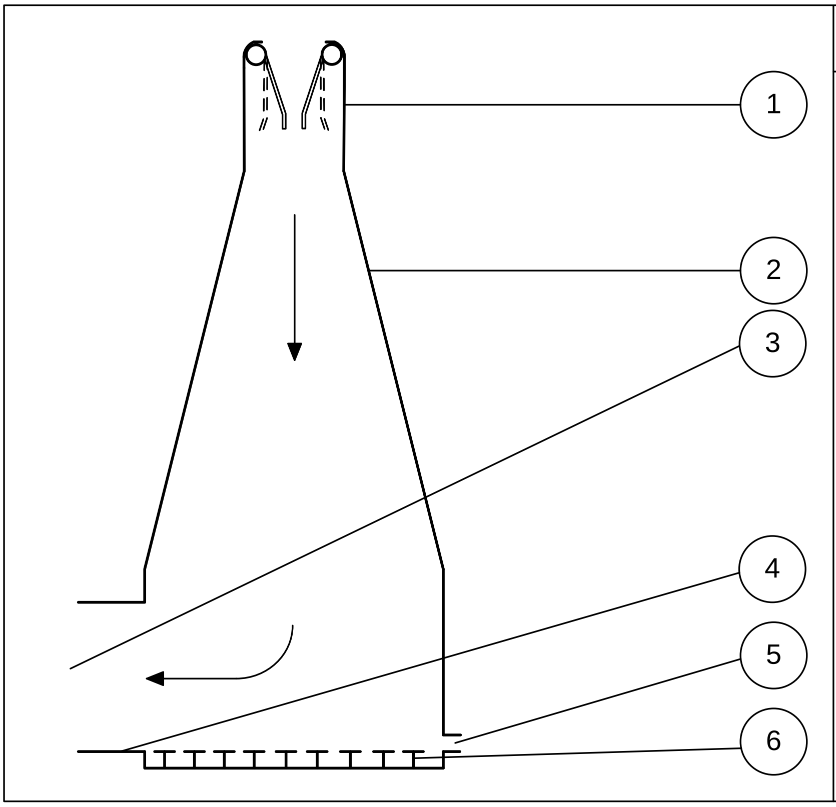
To determine an actuator size and a shaft diameter, a simple calculation can be done to determine the force on the blade and subsequently the moment require to operate it. Equation 7-33 indicates the equation used to determine these forces.

$$M = \left(\frac{1}{2}\rho_c v_g^2\right)\left(A_b l_b \frac{cos\theta}{2}\right) \tag{7-33}$$

7.2.10 Flooded Elbow

As discussed in the furnace water seal design, impingement is critical when a particle attaches to a liquid droplet as a result of interception or diffusion. Impingement plates often wear quickly due to the abrasive nature of the particulate, however there are solutions to impinge without the risk of wear. A flooded elbow is implemented, which is essentially a duct elbow with a water bed.

When the gas is accelerated downward in the high pressure venturi, the droplets have more inertia than the gas, making it harder to change direction with the gas stream. These droplets continue with a downward trajectory, and collides with the water’s surface. This impact allows the particle to move into the liquid droplet before it exits the elbow. Figure 7-13 indicates a typical arrangement of a flooded elbow.



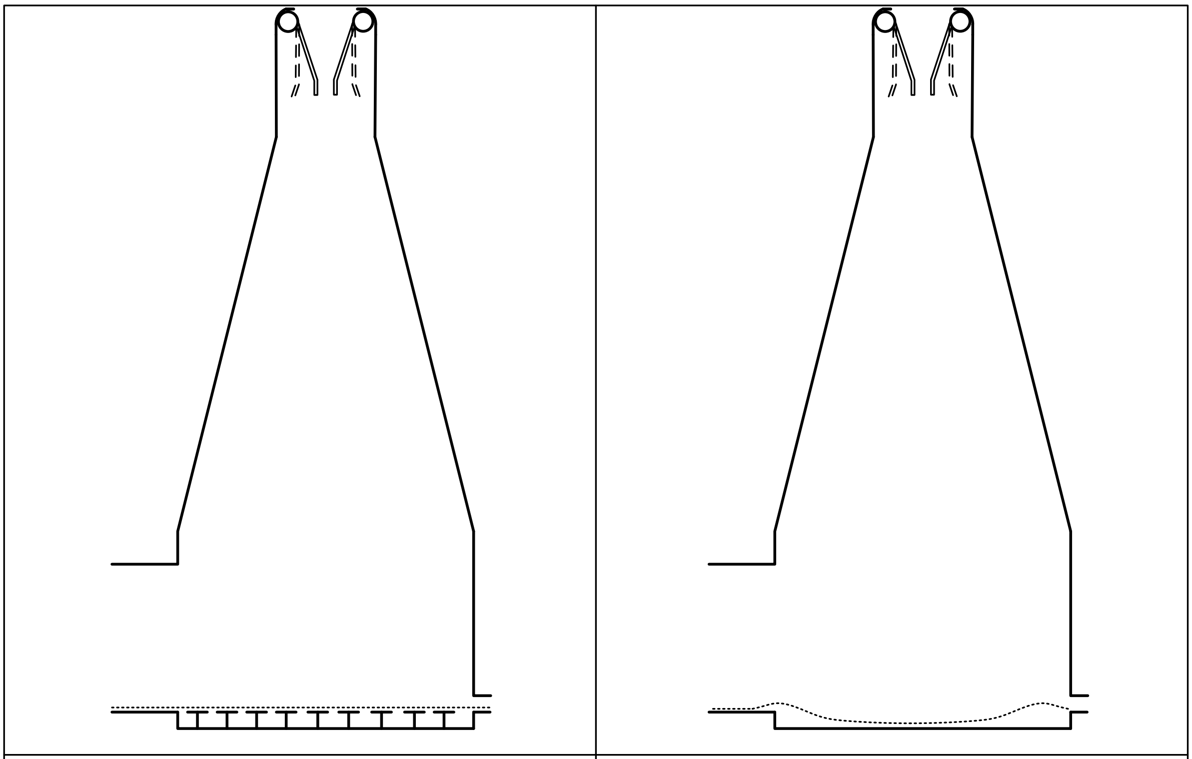
Components

1 – High pressure venturi
2 – Cold gas outlet
3 – Water seal
4 – Vessel shell
5 – Impingement plate
6 – Water outlet

Figure 7-13: Schematic of a flooded elbow

Problems can be experienced with flooded elbows if they are not designed correctly. If the water bed is too deep, the gas forces the liquid outward toward the side walls, resulting in a large meniscus shaped water surface. The water will deform to suit the flow pattern of the gas, eliminating a proper impingement surface. To account for this, steel protrusions can be inserted in the water bed, preventing the outward movement of water. This increases the impaction efficiency while still maintaining a water film on the steel surface to prevent wear.

The difference between a water bed with and without steel protrusion is indicated in Figure 7-14. Water is constantly pumped into the flooded elbow to prevent settlement between the steelwork as well as maintaining a filled water level.



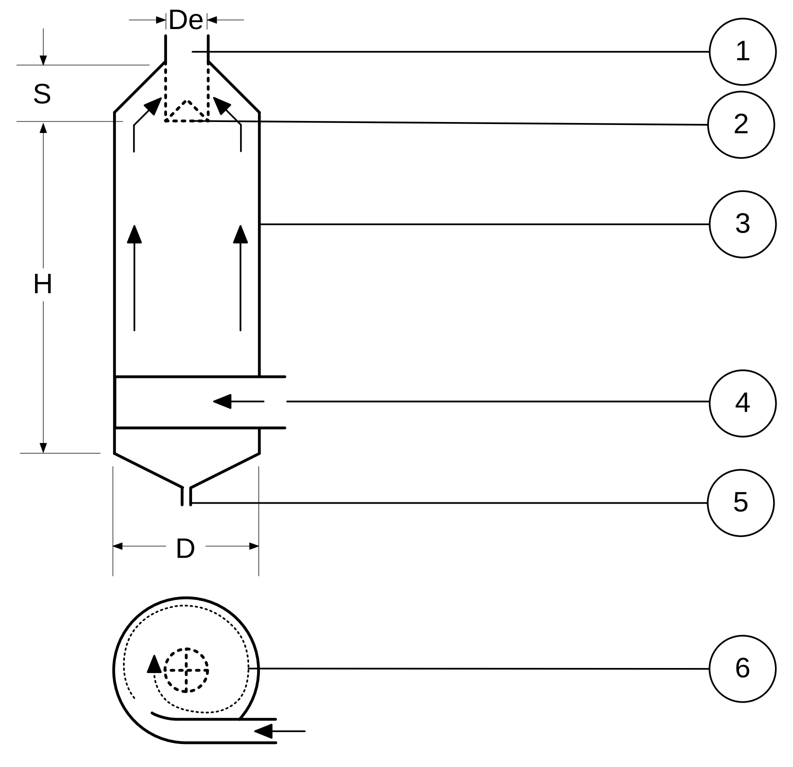
Wet elbow with impingement plates

Wet elbow without impingement plates

Figure 7-14: Comparison of a flooded elbow with and without impingement plates

7.2.11 Cyclonic Separator

Once the particulate has been forced into the liquid droplet, the majority of the droplets will still be in the gas stream, which need to be separated from the gas stream. A cyclonic separator is used in these scrubbers to eliminate the droplets by applying the law of centrifugal force. Figure 7-15 indicates a typical layout for a cyclonic separator.



Components

1 – Separator
2 – Conical diffuser
3 – Separator shell
4 – Gas inlet
5 – Water outlet
6 – Cyclonic air flow pattern

H – Cyclone height
D – Cyclone diameter
S – Outlet height
De – Outlet diameter

Figure 7-15: Schematic of a cyclonic separator

Designing the cyclonic separator requires a separation efficiency to be calculated. To initiate these design calculations, the number of revolutions in the separator needs to be determined, as indicated in equation 7-34.

$$N = \frac{1}{H_i}\left(H + \frac{S}{2}\right) \tag{7-34}$$

For the droplets to be collected, they must strike the outer shell of the separator while the gas moves across it within a certain amount of time. This time duration can be described as the gas residence time, and is defined in equation 7-35.

$$\Delta t = \frac{\pi\, D\, N}{v_g} \tag{7-35}$$

When the droplet enters the separator it is rapidly accelerated until it reaches its terminal velocity in a radial direction. The terminal velocity required to remove the droplet within a given time a certain distance *r* away from the shell. This is defined in equation 7-36.

$$v_t = \frac{r}{\Delta t} \tag{7-36}$$

The droplet drift velocity then needs to be determined as a function of droplet size.

$$v_t = \frac{(\rho_l - \rho_g) d_l^2 v_g^2}{9\,\mu\,D} \tag{7-37}$$

Substituting equation 7-35 into 7-36 eliminates Δt, and allows the equation to be rearranged to determine the droplet diameter d_l, indicated in equation 7-38.

$$d_l = \left[\frac{9\,\mu\,r}{\pi\,N\,v_g(\rho_l - \rho_g)}\right]^{\frac{1}{2}} \tag{7-38}$$

Equation 7-38 indicates the smallest droplet size in a cyclonic separator that will be collected with 100% efficiency. Lapple (1951) derived an equation for the collection of 50% of the droplets described in equation 7-38, and is expressed in equation 7-39, where d_{lc} is the "cut diameter of 50%.

$$d_{lc} = \left[\frac{9\,\mu\,r}{2\pi\,N\,v_g(\rho_l - \rho_g)}\right]^{\frac{1}{2}} \tag{7-39}$$

The collection efficiency is expressed in equation 7-40 for the droplet size.

$$\eta = \frac{1}{1 + \left(\frac{d_{lc}}{d_l}\right)^2} \tag{7-40}$$

When considering the cyclonic separator as a component in the scrubber system, the pressure loss needs to be calculated to determine a pressure balance across the system. The pressure drop is expressed in equation 7-41, and was developed by Shepherd and Lapple (1939), where ΔH is based on the cyclone dimension ratios and was developed by Dirgo (1988) and Ramachandran et al. (1991) and is expressed in equation 7-42, where *a* and *b* are the inlet dimensions.

$$\Delta p_c = \Delta H \left(\rho_g \frac{v_i^2}{2}\right) \tag{7-41}$$

A range of standard designs was developed to initiate a cyclone design by assuming geometrical ratios, which are indicated in table 7-10.

Table 7-10: Standard dimension ratios for cyclone design (Liu, 1997)

Duty	Derived	D	a/D	b/D	D_e/D	S/D	h/D	H/D	B/D	ΔH
High Efficiency	Stairmand	1	0.50	0.20	0.50	0.50	1.5	4.0	0.375	5.4
High Efficiency	Swift	1	0.44	0.21	0.40	0.50	1.4	3.9	0.40	9.2
General Purpose	Lapple	1	0.50	0.25	0.50	0.63	2.0	4.0	0.25	8.0
General Purpose	Swift	1	0.50	0.25	0.50	0.60	1.75	3.75	0.40	7.6
Consensus	Stern et al.	1	0.45	0.20	0.50	0.63	0.75	2.0	-	-
High Volume	Stairmand	1	0.75	0.38	0.75	0.88	1.5	4.0	0.38	7.2
High Volume	Swift	1	0.80	0.35	0.75	0.85	1.7	3.7	0.40	7.0

$$\Delta H = 20\left(\frac{ab}{D_e^2}\right)\left[\frac{\left(\frac{S}{D}\right)}{\left(\frac{H}{D}\right)\left(\frac{h}{D}\right)\left(\frac{B}{D}\right)}\right] \qquad (7\text{-}42)$$

A high efficiency and high volume cyclone was derived by Stairmand (1951) and Swift (1969). A general purpose cyclone was derived by Lapple (1951) and Swift (1969), and a consensus was derived by Stern et al. (1956).

Due to the liquid droplet size generated in the high pressure venturi a high efficiency cyclone will be used. The Stairmand derivation is selected, as the ΔH value is less than that of Swift, which reduces the pressure drop across the cyclone, subsequently reducing the power consumption required to displace the gas. The sacrifice in efficiency is negligible compared to the power that is saved.

By substituting the ratios derived by Stairmand into equation 7-42 and solving the previous cyclone equations iterative, the results returned are indicated in table 7-11.

Table 7-11: Results to determine the pressure drop across the cyclone

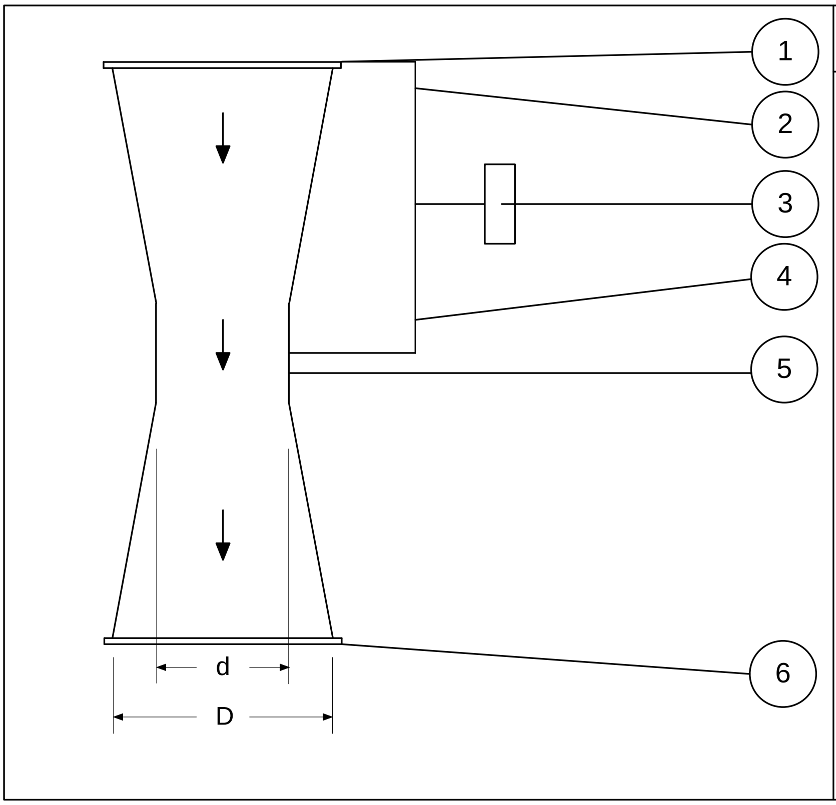
Variable	Result	Unit
d_L	1.271×10^{-5}	*m*
ΔH	4.63	-
N	12	-
Δt	476	*s*
v_g	14.89	*m/s*
v_t	2.101×10^{-5}	*m/s*
ρ_{gas}	1.107	*kg/m³*
ρ_{liq}	1900.00	*kg/m³*
μ_{gas}	1.802×10^{-5}	*Pa.s*
Δp_c	568	*Pa*
η	66.7	*%*

The pressure drop Δp_c will be used in the power requirement calculation is section 7.2.13. The elimination efficiency η of the cyclone is a low value only in the event that droplets do not attached to each other before reaching the cyclone. The flooded elbow induces droplet merging, which increases the cyclone efficiency. The value in table 7-11 is the worst case efficiency, and therefore the assumption can be made that $\eta > 66.7\%$.

7.2.12 Differential Pressure Flow Meter

During the operation of the scrubber plant it is important to maintain stable operating conditions. Two parameters that are critical to stable operation are the system flow and pressure, therefore a reliable flow meter needs to be implemented to reflect reliable conditions.

Due to the possible particulate matter and water in the system after the cyclonic separator, the flow meter needs to be resilient against build-up and clogging. A suitable device is a differential pressure venturi flow meter. The design is similar to that of the primary and high pressure venturis, however the task is to induce a pressure loss that will not affect the system pressure. Figure 7-16 indicates a typical layout of a venturi flow meter.



Components

1 – Inlet
2 – High pressure line
3 – Differential pressure meter
4 – Low pressure line
5 – Reduced area
6 – Outlet

d – Reduced duct diameter
D – Main duct diameter

Figure 7-16: Schematic of a venturi flow meter

Bernoulli's law is used to calculate the velocity in the reduced duct, where the main duct and reduced duct diameters are used to determine the effect of gas compressibility. Once the velocity has been determined, equation 7-43 is applied to calculate the flow rate.

$$Q_g = v_g \, A_{reduced\ duct} \tag{7-43}$$

The downward arrangement of the flow meters assists to clean itself from any build-up on the inside wall. Also, moisture that may collect on the inside of the wall will drain away instead of settle.

7.2.13 Main Fan Train

The fans can be described as the "heart" of the scrubber plant, as they allow the movement of gas to take place. Fan operation in the plant is critical, as production of the furnace cannot commence at full load if the scrubber plant is offline. Two fain trains are typically installed in parallel with change-over valves, of which one train is for stand-by. This also assists with maintenance and servicing of the fans or during repairs.

Fan selection is a simple process, which is governed by the gas power required to operate. This is defined in equation 7-44, where p_{sys} is the total pressure across the scrubber system and Q_c is a contingency for stability.

$$P_g = (Q_g + Q_c)p_{sys} \tag{7-44}$$

Due to the fluctuations in furnace pressure a gas flow rate contingency is incorporated into the gas power requirement. This allows the fans a larger range of control, as the gas can be recirculated if the furnace yields less gas, or extract more gas if the yield is greater.

The electrical power demand of the process is the incorporated efficiency of the fan and the electrical motor into equation 7-42, and is expressed in equation 7-45.

$$P_g = \frac{(Q_g + Q_c)p_{sys}}{\eta_{fan}\eta_{motor}} \tag{7-45}$$

The total system pressure needs to be determined to evaluate the fan selection. Each component's pressure loss is indicated in table 7-12.

Table 7-12: Pressure losses of each system component

Component	**Pressure Loss** *[Pa]*	**Flow Rate** *[Am³/s]*	**Gas Power** *[kW]*
Primary venturi	2 448.00	4.965	12.15
Furnace water seal	258.00	4.965	1.28
High pressure venturi	18 274.00	6.206	113.40
Cyclonic separator	568.00	6.206	3.52
Ducting	752.00	6.206	4.66
Desired outlet pressure	3000.00	6.206	18.61
Total	**25 300.00**	**6.071**	**153.62**

7.2.14 Furnace Pressure Control Damper

To ensure a stable furnace pressure a sacrifice needs to be made in the form of residual gas. The aforementioned contingency for the flow rate of the system is used as a buffer; more gas passes though the scrubber than necessary.

The furnace pressure control damper determines whether gas is recirculated through the scrubber, or expelled through the clean gas stack. This additional range of operation allows scrubber to control the gas flow extracted from the furnace very accurately, allowing for a safe working system. Typically a 25% contingency is added to the forecasted gas flow rate, which is indicated in table 7-10.

The selection of the damper is dependent on the range of accuracy required; a butterfly damper is most commonly used and has a very limited range of control, whereas an iris-arrangement damper controls over a large flow rate range, but is a very costly piece of equipment. Whichever damper type is selected, the most important feature is the speed of operation. Due to the natural instability of a furnace, the quicker the response of the damper, the more stable the pressure.

The furnace pressure control damper can be regarded as the most important component in the scrubber, as an unstable furnace is considered hazardous operation.

7.2.15 Recirculation Ducting

The furnace control damper is located at the inlet of the recirculation ducting, and the outlet is located above the high pressure venturi inlet. This is to allow for the largest possible pressure difference in the duct to ensure that the responsiveness of the system is as quick as possible.

In addition to furnace control, the recirculation of gas allows a portion to be re-scrubbed, further increasing the collection efficiency and reducing particulate emissions.

7.2.16 Distribution Gas Shut-Off Valve

Data collected in Section 5 indicates the gas composition of the furnace off-gas; the gases can be analysed in their volume fractions to determine the internal energy, indicated in table 7-13.

Table 7-13: Gas internal energy

Gas Internal Energy					
Gas	Percentage	Density *$[kg/m^3]$*	Mass Frac. *[kg/s]*	LHV *[kJ/kg]*	Power *[kW]*
Carbon Monoxide	61.24 %	1.1294	3.4371	1 0160.40	34 922.00
Carbon Dioxide	12.74 %	1.7745	1.1234	-	-
Hydrogen	9.77 %	0.0813	0.0395	120 091.89	4 739.10
Oxygen	1.10 %	1.2902	0.0705	-	-
Nitrogen	14.4 %	1.1295	0.8083	-	-
Methane	0.71 %	0.6468	0.0288	49 855.30	1 1378.00
Total	**100.00%**		**5.5016**		**40 799.00**

It is clear from the data in Table 7-11 that there is a significant amount of thermal energy in the gas, close to 40.8 *MW* of power. This energy can be utilized in many different ways to recover some of the power input into the furnace.

In the industry, some furnace companies utilize the off-gas to heat the charged material before it is added to the furnace. This allows the pre-reduction of the manganese oxide, reducing the energy consumption of the process per unit. This is a viable method of optimizing the overall process to save on energy costs, as well as reduce production time.

Other companies post combust the off-gas in a steam boiler, which feeds a steam turbine. The turbine drives a generator, which supplies electricity to the plant's grid. This method is also a viable alternative to save costs by utilizing by-products from the furnace smelting process.

The distribution gas shut-off valve controls whether gas is flared through the clean gas stack, or distributed towards a post combustion process. Typically this valve is accompanied by a spade, so that the duct can be positively isolated for maintenance purposes.

7.2.17 Stack Flow Control Damper

Furnace pressure instability occurs when more or less gas is extracted than yielded. To control this, a control damper is utilized to maintain a positive pressure on at the outlet of the main fans. This serves the purpose of determining whether enough gas is being expelled though the clean gas stack.

Also, the positive pressure created at the main fain outlet increases the differential pressure between the recirculation ducting inlet and the high pressure venturi inlet. This assists to further accelerate the recirculated gas, increasing the responsiveness of the change in furnace pressure when the furnace control damper rotates.

Generally a 3.0 *kPa* positive pressure is used as a set point for the stack flow control damper. This allows for a significant buffer the gas yield in the furnace fluctuates.

7.2.18 Clean Gas Stack

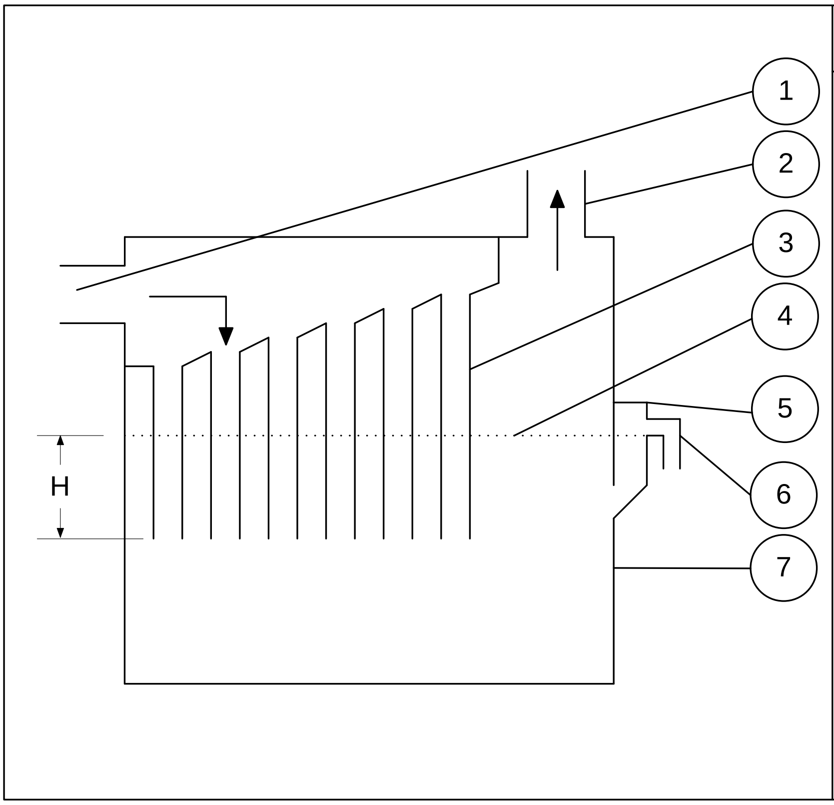
Essentially the exhaust of the scrubber, the clean gas is used to expel the gas into the atmosphere at a safe elevation, so that the gas cannot affect the surrounding environment.

7.2.19 Reflux Water Seal

A scrubber plant has many interlocks which need to be healthy for operation. If an interlock were to fail, the scrubber would trip as a protection mechanism. A scrubber may trip many times during a shift, which is a hazardous situation, as the gas cannot be displaced and is trapped within the scrubber. The gas is hot compared to the atmospheric air; the hot gas begin to cool when stagnant in the scrubber. Clapeyron's law states that if the temperature of a gas decreases in a constant volume, the pressure decreased proportionally (Clapeyron, 1834).

The resultant vacuum within the scrubber can draw air into the system through any open orifice; if the correct stoichiometric ratio is achieved, the gas will explode. To prevent this from happening, as reflux water seal is incorporated at the base of the clean gas stack to prevent air ingress under static conditions. Its operating principal is similar to that of the furnace water seal in that is uses a head of water to create a seal. However, the gas stream is continuously passed through the water during operation, which demands a much lower pressure head of water compared to that of the furnace water seal. A typical reflux seal design is indicated in Figure 7-17.

The operating principal is that the downward pipes diffuse the gas through the water, reducing turbulence and resultant forces, rather than having one large duct in a water bed. The reduction of turbulence reduces the chances of the water being displaced outward, forming a meniscus shaped water surface, forcing all the water though the weir overflow, eliminating the water seal head.



Components

1 – Inlet
2 – Outlet
3 – Downward pipe diffuser
4 – Water level
5 – Weir
6 – Overflow drain
7 – Reflux seal shell

H – Water seal head

Figure 7-17: Schematic of a reflux water seal

7.2.20 Primary Seal Pot

The primary seal pot incorporates a head of water to seal the scrubber from the atmosphere. The principal is similar to that of the furnace water seal, as the same equations are used to design the required pressure head.

During operation, the liquid injected into the primary and high pressure venturi is drained to the main seal pot. The new liquid that enters the seal pot displace the existing body of water, without letting gases escape to atmosphere. It is critical that the main seal pot is tested for leaks regularly, as the vacuum at the high pressure venturi can draw a large amount of air into the scrubber in a very short period of time, with catastrophic consequences. Figure 7-18 indicates a typical seal pot arrangement.

Liquid is continuously added to the seal pot to ensure that the head is maintained. Liquid should be added from the bottom of the seal bot to create turbulence, preventing settlement of particulate. The seal pot is sized as a function of water added to both the primary and high pressure venturis, as they supply the seal pot with relatively large quantities of water.

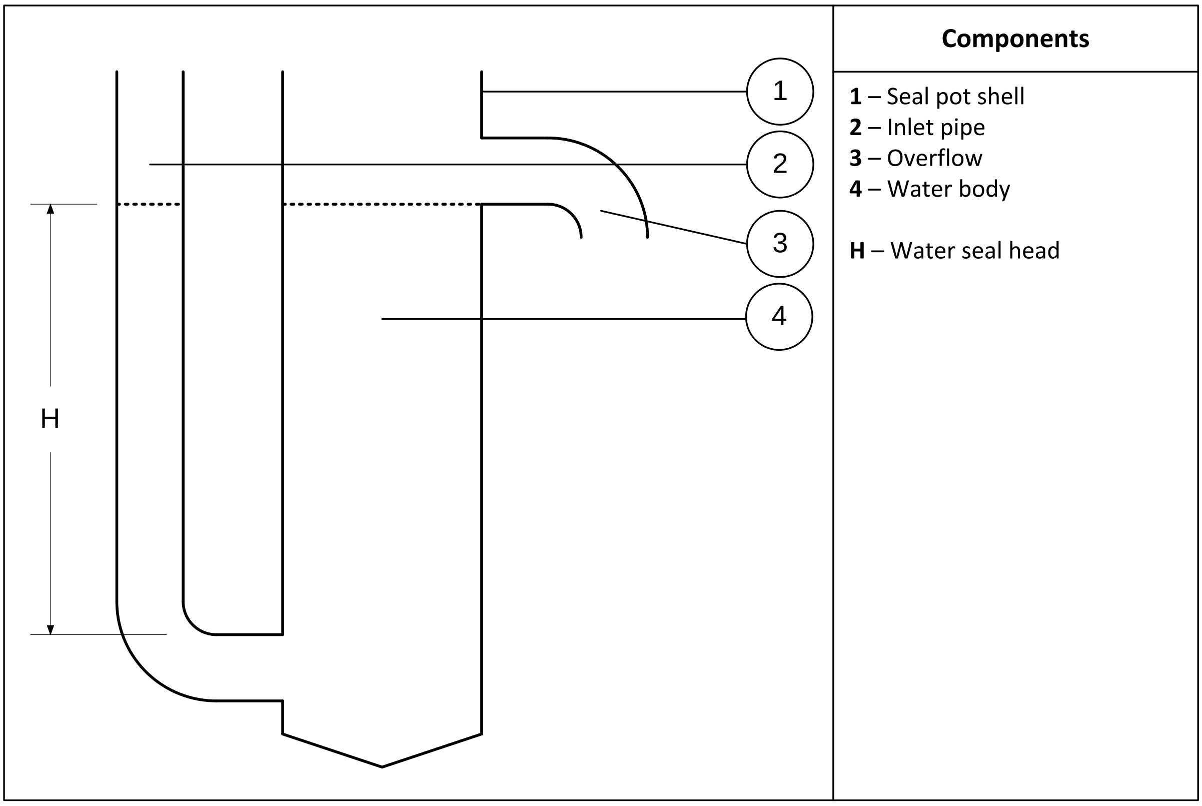


Figure 7-18: Schematic of a seal pot

7.2.21 Fan Seal Pot

The fan seal pot is based on the same principal as the main seal pot, however it is significantly smaller as it does not need to handle a continuous flow of water. Each fan typically has its own dedicated seal pot to assist with maintenance.

7.2.22 Clean Gas Flare Tip

Designed similarly to that of the raw gas, the clean gas flare tip makes use of the same features and components described for that of the raw gas. There are, however, dissimilarities specifically the diameter, as the volumetric flow rate is significantly less due to the temperature difference. Also, the material is of a lower grade as it does not need to withstand high temperatures, however the serrated tip is still made from a heat resistant material.

7.2.23 Emergency Water Tank

The emergency water tank is designed to hold enough water to fill the furnace water seal twice. It is located directly above the water seal, so that the height difference allows a larger pressure for the water to be injected.

In the event of an emergency where the water supply is cut off instantly, or all other safety mechanisms fail, the emergency tank will discharge its payload into the furnace water seal. The tank's outlet pipe is fitted with a spring-loaded fail-open valve, i.e. it will open automatically if the compressed air or electrical supply were to fail.

8 Post-Design Experimentation

8.1 Primary Venturi Temperature

To determine the effectiveness of the primary venturi design the inlet and outlet temperatures need to be compared with that of the actual readings. The inlet and outlet temperatures are sampled continuously over a period of 60 hours with hourly intervals, which is sufficient data to evaluate the forecasted conditions. The temperatures are plotted in Figure 8-1, indicating a summary of the process methodology.

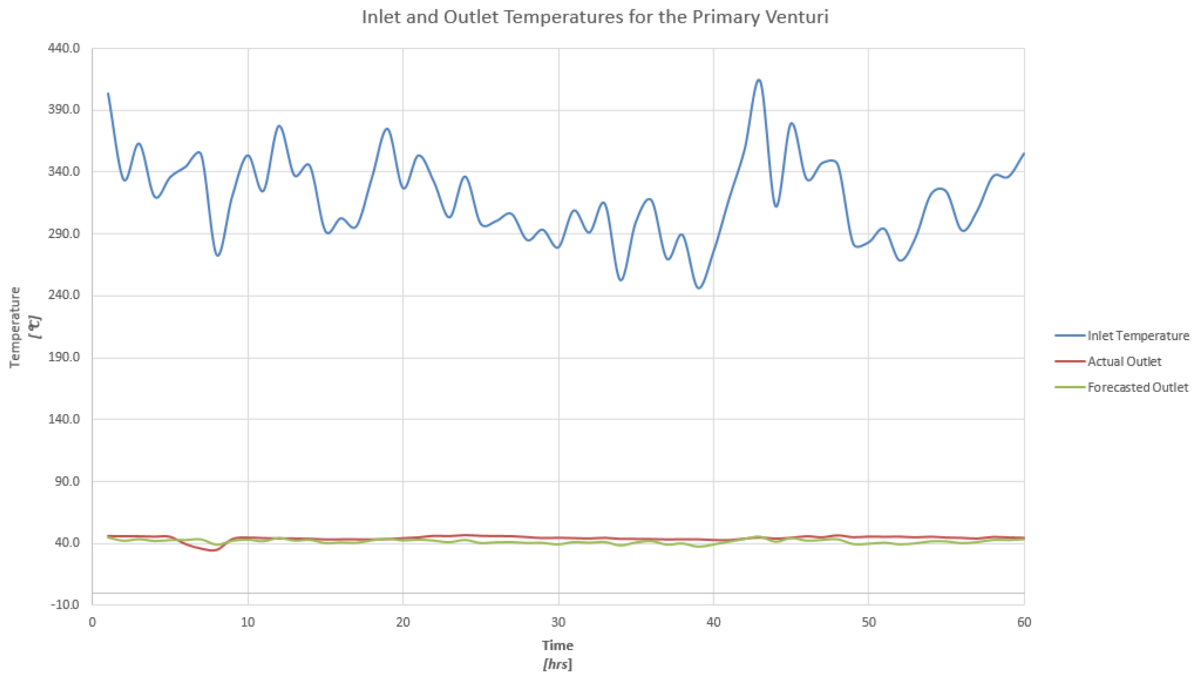


Figure 8-1: Comparison of the furnace and primary venturi temperatures

To ensure that the equations used in Section 7.2 the primary venturi outlet temperature needs to be compared with the actual readings to determine an error. These values are indicated in table 8-1.

Table 8-1: Comparison of forecasted versus sampled temperatures

Temperature Comparison				
	Venturi Inlet [℃]	Outlet Forecast [℃]	Outlet Actual [℃]	Deviation [℃]
Average	315.70	41.60	44.50	2.90
Maximum	409.00	45.80	47.10	7.50
Minimum	243.40	37.10	34.80	0.30
Standard deviation	34.28	1.79	2.09	2.55

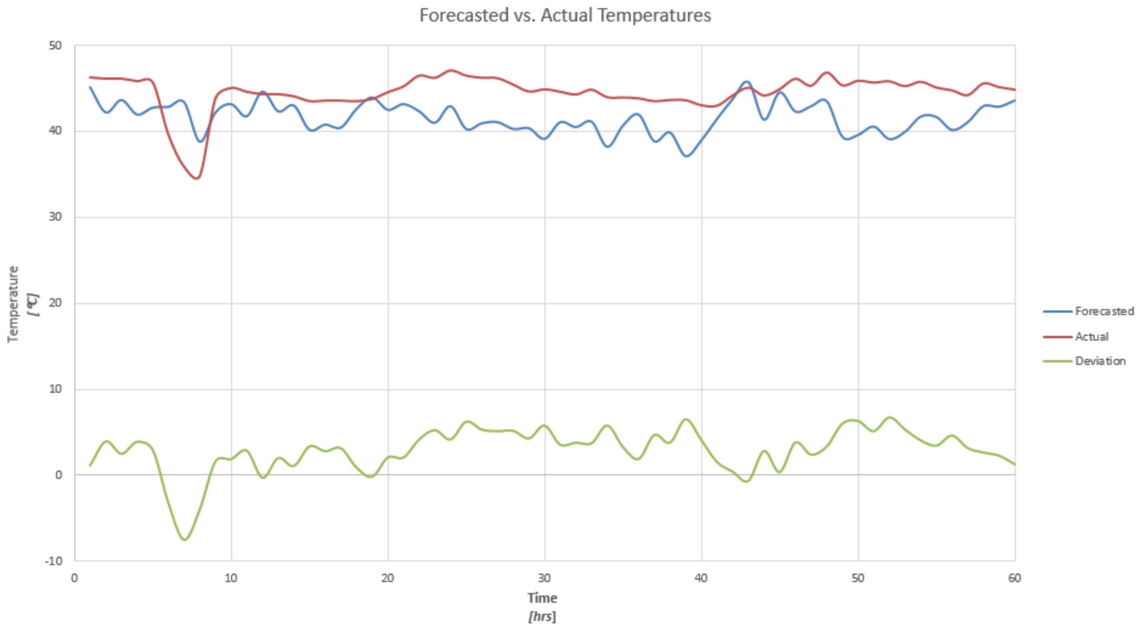


Figure 8-2: Comparison between the forecasted and sampled temperatures

The difference in forecasted and actual temperatures is plotted in Figure 8-2. This gives a graphical representation of the error magnitude.

8.2 Overall Scrubber Collection Efficiency

To ensure that the scrubber conforms to environmental legislation, isokinetic sampling needs to be conducted annually. This ensures that the scrubber plant does not lose efficiency over the course of its lifetime, and also for deviations in efficiency to be identified regularly for remediation.

Isokinetic sampling was conducted over a period of two days, and a verified total of six samples were sent off for laboratory testing and evaluation. A comparison between the forecasted and actual sampled results are indicated in table 8-2.

Table 8-2: Forecasted versus actual collection efficiency

Collection Efficiency Comparison				
	Legal Limit *[mg/Nm^3]*	Forecasted Emissions *[mg/Nm^3]*	Actual Emissions *[mg/Nm^3]*	Deviation *[mg/Nm^3]*
Sample 1	100.00	71.57	33.60	37.97
Sample 2	100.00	71.57	53.30	18.27
Sample 3	100.00	71.57	35.30	36.27
Sample 4	100.00	71.57	52.40	19.17
Sample 5	100.00	71.57	50.60	20.97
Sample 6	100.00	71.57	49.30	22.27

9 Budget

When budgeting for a plant of this magnitude it is difficult to accurately predict a cost, as prices constantly fluctuate. Also, items that have longer lead-time can affect the cost of those with a shorter lead-time, as escalation can have a negative effect over the final cost. It is therefore critical to ensure that budgeting is done over a short period of time, and that a detailed and accurate buy-in schedule be generated. For the purpose of this study, only a bill of quantities will be drafted, as a cost per unit will only be accurate at the time of evaluation.

9.1 Bill of Quantities

A typical high-level bill of quantities incorporates a breakdown of the plant requirements, to summarise the necessary financial components. Table 9-1 indicates the items required for the execution of a turn-key wet venturi scrubber plant project. A cost is not indicated for the items, as a comprehensive budget breakdown can be found in appendix 11.4.

Table 9-1: Summarised requirements for a wet venturi scrubber

Wet Venturi Scrubber Requirements	
Description	*Cost*
Engineering	R 6 275 625.00
Ducting and Stack	R 21 250 777.50
Emergency Stack Equipment	R 2 857 470.00
Primary Venturi Equipment	R 4 698 290.00
Scrubber Ducting	R 518 450.00
High Pressure Venturi Equipment	R 2 387 287.50
Reflux Water Seal	R 3 236 250.00
Main Fan Trains	R 46 667 340.00
Control and Isolation Dampers	R 4 030 025.00
Flare Tip Systems	R 8 357 108.00
Support Structures	R 2 810 400.00
Total Cost	**R 103 089 023.00**

9.2 Financial Costing

Failure to comply with environmental guidelines can result in hefty penalties, which can have a detrimental effect on business. Also, the Department of Environmental Affairs has the authority to cease all production on a furnace that is non-compliant, over and above the penalties discussed in section 2. The lack of production with the current overheads of a furnace can cause bankruptcy within months, as labour legislation and customer demands still exist when a production license has been revoked.

The implementation of a scrubber plant is beneficial to both the environment and the financial wellbeing of a furnace production company. A financial viability model needs to be calculated to ensure that the return on production outweighs the cost of operation, along with capital required to conform to environmental legislation. Clean furnace off-gas can be used to generate power, to reduce furnace power consumption by pre-heating the charged material, which also encourages the implementation of an efficient scrubber system.

Although the majority of corporations rely on financial return to justify operation, we are obligated to ensure the wellbeing of the environment. This is often a costly exercise with a significant capital outlay, however the benefits are clearly justified when considering what the human race stands to lose.

10 Conclusion

Upon completion of the scrubber design the engineering, procurement and construction phases can commence, followed by commissioning and start-up. The commissioning of a scrubber plant is a process that requires patience and diligence. The hazardous nature of the furnace off-gas requires that all safety aspects are met, along with a certified commissioning procedure.

10.1 Commissioning Procedure

To commission a scrubber plant a step-by-step procedure needs to be followed, and each item is to be verified by at least two persons. This reduces the possibility of errors, which can have catastrophic consequences.

Table 10-1: Commissioning procedure for a wet venturi scrubber plant

Step	Procedure	Description
1	**Pressure testing**	Conduct a pressure test on the system by applying compresses air, approximately 1.25 times the operating pressure of the plant. This will ensure that the water seal in the seal pots remain intact. A pressure gauge is to be monitored for the duration of the test, so that a timeline can be determine as to how long depressurization takes. The time duration is to be in accordance with that of the specified test procedure, which varies from each end-user.
2	**Purging**	Once the pressure test has been conducted successfully, the scrubber needs to be purged of all air, to eliminate the possibility of an explosion within the system. This is done by displacing the air in the scrubber with post-combusted furnace off-gas.
2.1		Inspection hatches on the furnace roof are opened to allow air to enter the furnace.
2.2		One fan is then sped up to full speed and the liquid injection system on the primary and high pressure venturis is opened to the required velocity. The venturi throats are to remain in an open position until the purging is complete.
2.3		The furnace water seal is then drained allowing the furnace gas to be extracted. The air that is drawn into the furnace combusts above the charged material, and the CO is converted into CO_2.
2.4		Purging is to continue until the oxygen level on the gas analysers returns an acceptable value.
2.5		Purging has thus been completed, and the furnace inspection hatches can be closed. The scrubber plant with then continue to extract pure furnace off-gas, and is to be considered a hazardous system.
3	**Start-Up**	When one fan is running at full speed, the volumetric flow rate is the same as if all three fans were running, as a fan is a constant volume displacing

		component, and the total pressure is increases when more than one fan is in series.
3.1		One fan cannot overcome the pressure drop of both venturi throats at their operating position. Therefore their positions remain open as during the purging process.
3.2		The second and third fan are then started up to full speed, while the second and third fan are then started up to full speed, while the flow control damper remains only slightly open and the furnace pressure control damper fully open. This will allow the majority of gas to circulate, rather than being discharged through the stack.
3.3		Once all three fans are running full speed, the furnace pressure control damper needs to be set to an automatic controller, and the same for the flow control damper.
3.4		The system will then proceed to extract all the gas from the furnace at a constant flow rate, however the particulate elimination will only increase once the venturis are set to their operating positions.
3.5		Both the primary and high pressure venturis are set to their operating positions.
4	**Control**	The system is very forgiving in a dynamic application, as the controllers will compensate for any changes in the process parameters.

10.2 Evaluation of Post-Design Results

To determine whether the design is successful, the forecasted calculated results needs to be compared with the actual operating parameters.

10.2.1 Primary Venturi Temperatures

The forecasted average temperature difference across the primary venturi was calculated to be 274.1°C, resulting in an average outlet temperature of 41.6°C. For this forecast in temperature decrease to be verified, it was compared to a set of temperature readings taken of the same period.

Test results returned an average temperature difference across the primary venturi of 271.2°C, which indicates a mean deviation of 2.90° when considering the series. This deviation is as a result of variations in the system that cannot be predicted, however the control philosophy can mitigate the majority of these changes effectively.

When considering the graphs in Section 9 it is clear the gas has reached saturation when calculated with the method prescribed in Section 7. The verifications of the temperature samples with an insignificant difference in saturation temperature deems the method to be successful and highly accurate for future designs.

10.3 Overall Scrubber Collection Efficiency

When considering the legal requirement aspect of the design efficiency, it is important to ensure that the limitations will never be exceeded. For verification of the overall collection efficiency of the scrubber, the design efficiency needs to be compared with the results returned in Section 9.

Figure 10-1 indicates that the actual emissions of the scrubber is well below the required parameters. The difference between the design and actual collection efficiency is determined by the reaction within the furnace. The design parameters used were to remove a certain percentage of the lightest present element, carbon, thus increasing the efficiency of the scrubber in the presence of other particulate. This allows for a margin to be incorporated, as the worst case scenario would be if only carbon was extracted in the gas stream. The scrubber design would, however, be able to cater for this scenario and operating within the parameters set by legislation.

The *y-axis* in Figure 10-1 indicates a comparison of the emissions, which clearly shows that the actual scrubber emissions are less than that of both the legal and design requirements. When considering the collection efficiency in Section 9 it is clear that the required amount of particulate has been removed from the gas stream when calculated with the method prescribed in Section 7. The increase in collection efficiency verifies that the design method is accurate and successful, as well as incorporating a margin for the dynamic characteristic of a furnace.

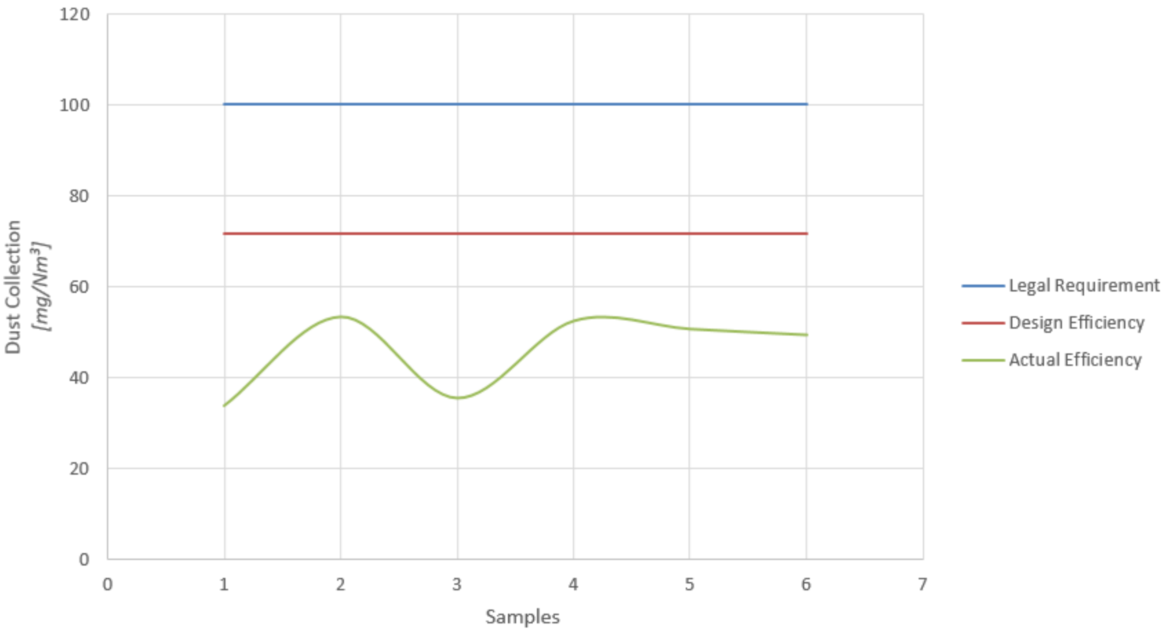


Figure 10-1: Comparison of the actual scrubber emissions versus the legal and design requirements

10.4 Closing

Immeasurable parameters prevent designing a scrubber that can perform the required task by adapting to the bare minimum for the required efficiencies. It is good engineering practice to design for the worst cases, thereby incorporating a margin for error during standard operating parameters. There is, however, a limit as to how much of a margin is added during the design phase, as each addition increases the overall cost of the plant. A balance needs to be obtained between the minimum design requirement and the longevity of the plant, based on financial implications.

When all these aspects are taken into account a true engineering challenge is presented, as it is an easy task to design an object when not adhering to practical and financial requirements. When systems are designed competitively in the industry it is critical to maintain an edge over the competition by making continual improvements to designs, thus optimizing the plant. This is a costly task, as the return on research and development is only marginal compared to new engineering concepts.

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11 Appendices

11.1 Particle Size Distribution Results at Different Furnace Loads

Table 11-1: Particle size distribution results at 6.2MW

Date	16-Jan-13
Furnace Power [MW]	6.20
Total Particles	2499
Min Size	0.7
Max Size	24.3
Arithmetic Mean	4.1
Geometric Mean	3.6

From	**To**	**Counts**	**Percentage**	**From**	**To**	**Counts**	**Percentage**
[μm]	*[μm]*		*[%]*	*[μm]*	*[μm]*		*[%]*
0.0	0.2	0	0.00%	8.0	8.2	5	0.20%
0.2	0.4	0	0.00%	8.2	8.4	10	0.40%
0.4	0.6	0	0.00%	8.4	8.6	9	0.36%
0.6	0.8	21	0.84%	8.6	8.8	14	0.56%
0.8	1.0	2	0.08%	8.8	9.0	1	0.04%
1.0	1.2	34	1.36%	9.0	9.2	5	0.20%
1.2	1.4	48	1.92%	9.2	9.4	5	0.20%
1.4	1.6	112	4.48%	9.4	9.6	6	0.24%
1.6	1.8	14	0.56%	9.6	9.8	2	0.08%
1.8	2.0	90	3.60%	9.8	10.0	1	0.04%
2.0	2.2	49	1.96%	10	11	17	0.68%
2.2	2.4	77	3.08%	11	12	7	0.28%
2.4	2.6	47	1.88%	12	13	7	0.28%
2.6	2.8	187	7.48%	13	14	0	0.00%
2.8	3.0	134	5.36%	14	15	1	0.04%
3.0	3.2	254	10.16%	15	16	2	0.08%
3.2	3.4	56	2.24%	16	17	2	0.08%
3.4	3.6	45	1.80%	17	18	2	0.08%
3.6	3.8	50	2.00%	18	19	1	0.04%
3.8	4.0	229	9.16%	19	20	1	0.04%
4.0	4.2	134	5.36%	20	21	2	0.08%
4.2	4.4	40	1.60%	21	22	1	0.04%
4.4	4.6	152	6.08%	22	23	1	0.04%
4.6	4.8	39	1.56%	23	24	1	0.04%
4.8	5.0	81	3.24%	24	25	1	0.04%
5.0	5.2	20	0.80%				
5.2	5.4	148	5.92%				
5.4	5.6	16	0.64%				
5.6	5.8	29	1.16%				
5.8	6.0	55	2.20%				
6.0	6.2	49	1.96%				
6.2	6.4	4	0.16%				
6.4	6.6	11	0.44%				
6.6	6.8	76	3.04%				
6.8	7.0	13	0.52%				
7.0	7.2	5	0.20%				
7.2	7.4	44	1.76%				
7.4	7.6	0	0.00%				
7.6	7.8	7	0.28%				
7.8	8.0	23	0.92%				

Table 11-2: Particle size distribution results at 9.0MW

Date	08-Feb-13
Furnace Power [MW]	9.00
Total Particles	2325
Min Size	0.7
Max Size	89.7
Arithmetic Mean	6
Geometric Mean	4.4

From	**To**	**Counts**	**Percentage**	**From**	**To**	**Counts**	**Percentage**
[μm]	*[μm]*		*[%]*	*[μm]*	*[μm]*		*[%]*
0.0	0.2	0	0.00%	8.0	8.2	5	0.22%
0.2	0.4	0	0.00%	8.2	8.4	23	0.99%
0.4	0.6	0	0.00%	8.4	8.6	11	0.47%
0.6	0.8	47	2.02%	8.6	8.8	29	1.25%
0.8	1.0	3	0.13%	8.8	9.0	1	0.04%
1.0	1.2	75	3.23%	9.0	9.2	10	0.43%
1.2	1.4	62	2.67%	9.2	9.4	13	0.56%
1.4	1.6	106	4.56%	9.4	9.6	21	0.90%
1.6	1.8	21	0.90%	9.6	9.8	5	0.22%
1.8	2.0	67	2.88%	9.8	10.0	8	0.34%
2.0	2.2	44	1.89%	10	11	62	2.67%
2.2	2.4	77	3.31%	11	12	41	1.76%
2.4	2.6	30	1.29%	12	13	46	1.98%
2.6	2.8	98	4.22%	13	14	35	1.51%
2.8	3.0	95	4.09%	14	15	25	1.08%
3.0	3.2	146	6.28%	15	16	16	0.69%
3.2	3.4	31	1.33%	16	17	11	0.47%
3.4	3.6	16	0.69%	17	18	15	0.65%
3.6	3.8	29	1.25%	18	19	11	0.47%
3.8	4.0	115	4.95%	19	20	9	0.39%
4.0	4.2	66	2.84%	20	21	7	0.30%
4.2	4.4	26	1.12%	21	22	10	0.43%
4.4	4.6	104	4.47%	22	23	7	0.30%
4.6	4.8	27	1.16%	23	24	2	0.09%
4.8	5.0	72	3.10%	24	25	5	0.22%
5.0	5.2	11	0.47%	25	26	4	0.17%
5.2	5.4	108	4.65%	26	27	4	0.17%
5.4	5.6	16	0.69%	27	28	3	0.13%
5.6	5.8	31	1.33%	28	29	4	0.17%
5.8	6.0	33	1.42%	29	30	3	0.13%
6.0	6.2	51	2.19%	30	31	4	0.17%
6.2	6.4	9	0.39%	31	32	1	0.04%
6.4	6.6	7	0.30%	32	33	3	0.13%
6.6	6.8	77	3.31%	33	34	2	0.09%
6.8	7.0	31	1.33%	34	35	2	0.09%
7.0	7.2	4	0.17%	35	36	2	0.09%
7.2	7.4	54	2.32%	36	37	1	0.04%
7.4	7.6	0	0.00%	37	38	1	0.04%
7.6	7.8	21	0.90%	38	39	2	0.09%
7.8	8.0	44	1.89%	39	89	6	0.26%

Table 11-3: Particle size distribution results at 15.0MW

Date	15-Feb-13
Furnace Power [MW]	15.00
Total Particles	2117
Min Size	0.7
Max Size	90
Arithmetic Mean	4.6
Geometric Mean	3.3

From	**To**	**Counts**	**Percentage**	**From**	**To**	**Counts**	**Percentage**
[μm]	*[μm]*		*[%]*	*[μm]*	*[μm]*		*[%]*
0.0	0.2	0	0.00%	8.0	8.2	10	0.47%
0.2	0.4	0	0.00%	8.2	8.4	11	0.52%
0.4	0.6	0	0.00%	8.4	8.6	16	0.76%
0.6	0.8	78	3.68%	8.6	8.8	13	0.61%
0.8	1.0	2	0.09%	8.8	9.0	2	0.09%
1.0	1.2	77	3.64%	9.0	9.2	8	0.38%
1.2	1.4	78	3.68%	9.2	9.4	10	0.47%
1.4	1.6	169	7.98%	9.4	9.6	9	0.43%
1.6	1.8	23	1.09%	9.6	9.8	6	0.28%
1.8	2.0	120	5.67%	9.8	10.0	6	0.28%
2.0	2.2	66	3.12%	10	11	38	1.79%
2.2	2.4	110	5.20%	11	12	23	1.09%
2.4	2.6	64	3.02%	12	13	16	0.76%
2.6	2.8	131	6.19%	13	14	15	0.71%
2.8	3.0	84	3.97%	14	15	11	0.52%
3.0	3.2	84	3.97%	15	16	3	0.14%
3.2	3.4	66	3.12%	16	17	6	0.28%
3.4	3.6	28	1.32%	17	18	7	0.33%
3.6	3.8	51	2.41%	18	19	11	0.52%
3.8	4.0	70	3.31%	19	20	3	0.14%
4.0	4.2	55	2.60%	20	21	6	0.28%
4.2	4.4	54	2.55%	21	22	3	0.14%
4.4	4.6	45	2.13%	22	23	1	0.05%
4.6	4.8	36	1.70%	23	24	2	0.09%
4.8	5.0	46	2.17%	24	25	1	0.05%
5.0	5.2	16	0.76%	25	26	1	0.05%
5.2	5.4	59	2.79%	26	27	4	0.19%
5.4	5.6	12	0.57%	27	28	2	0.09%
5.6	5.8	26	1.23%	28	29	0	0.00%
5.8	6.0	27	1.28%	29	30	1	0.05%
6.0	6.2	37	1.75%	30	31	2	0.09%
6.2	6.4	12	0.57%	31	32	0	0.00%
6.4	6.6	9	0.43%	32	33	1	0.05%
6.6	6.8	41	1.94%	33	34	1	0.05%
6.8	7.0	18	0.85%	34	35	1	0.05%
7.0	7.2	9	0.43%	35	36	0	0.00%
7.2	7.4	22	1.04%	36	37	1	0.05%
7.4	7.6	4	0.19%	37	38	0	0.00%
7.6	7.8	12	0.57%	38	39	0	0.00%
7.8	8.0	19	0.90%	39	91	6	0.28%

Table 11-4: Particle size distribution results at 30.0MW

Date	28-Feb-13
Furnace Power [MW]	30.00
Total Particles	2300
Min Size	0.7
Max Size	255
Arithmetic Mean	5
Geometric Mean	3.7

From	**To**	**Counts**	**Percentage**	**From**	**To**	**Counts**	**Percentage**
[µm]	*[µm]*		*[%]*	*[µm]*	*[µm]*		*[%]*
0.0	0.2	0	0.00%	8.0	8.2	7	0.30%
0.2	0.4	0	0.00%	8.2	8.4	15	0.65%
0.4	0.6	0	0.00%	8.4	8.6	12	0.52%
0.6	0.8	46	2.00%	8.6	8.8	19	0.83%
0.8	1.0	3	0.13%	8.8	9.0	6	0.26%
1.0	1.2	61	2.65%	9.0	9.2	10	0.43%
1.2	1.4	76	3.30%	9.2	9.4	10	0.43%
1.4	1.6	141	6.13%	9.4	9.6	20	0.87%
1.6	1.8	27	1.17%	9.6	9.8	7	0.30%
1.8	2.0	120	5.22%	9.8	56	9	0.39%
2.0	2.2	67	2.91%	10	38	28	1.22%
2.2	2.4	122	5.30%	11	19	19	0.83%
2.4	2.6	47	2.04%	12	25	12	0.52%
2.6	2.8	113	4.91%	13	15	15	0.65%
2.8	3.0	94	4.09%	14	13	16	0.70%
3.0	3.2	137	5.96%	15	17	10	0.43%
3.2	3.4	59	2.57%	16	10	9	0.39%
3.4	3.6	23	1.00%	17	12	9	0.39%
3.6	3.8	59	2.57%	18	4	7	0.30%
3.8	4.0	139	6.04%	19	4	8	0.35%
4.0	4.2	62	2.70%	20	6	8	0.35%
4.2	4.4	28	1.22%	21	6	6	0.26%
4.4	4.6	63	2.74%	22	2	9	0.39%
4.6	4.8	38	1.65%	23	4	9	0.39%
4.8	5.0	70	3.04%	24	2	3	0.13%
5.0	5.2	18	0.78%	25	3	6	0.26%
5.2	5.4	91	3.96%	26	2	5	0.22%
5.4	5.6	13	0.57%	27	2	1	0.04%
5.6	5.8	34	1.48%	28	3	2	0.09%
5.8	6.0	39	1.70%	29	0	1	0.04%
6.0	6.2	26	1.13%	30	4	1	0.04%
6.2	6.4	12	0.52%	31	0	4	0.17%
6.4	6.6	7	0.30%	32	2	2	0.09%
6.6	6.8	48	2.09%	33	1	0	0.00%
6.8	7.0	18	0.78%	34	0	1	0.04%
7.0	7.2	3	0.13%	35	1	2	0.09%
7.2	7.4	34	1.48%	36	0	0	0.00%
7.4	7.6	5	0.22%	37	1	1	0.04%
7.6	7.8	18	0.78%	38	1	1	0.04%
7.8	8.0	23	1.00%	39	251	1	0.04%

Table 11-5: Particle size distribution results at 42.0MW

Date	08-Mar-13
Furnace Power [MW]	42.00
Total Particles	2419
Min Size	0.7
Max Size	47.9
Arithmetic Mean	5
Geometric Mean	3.6

From	To	Counts	Percentage	From	To	Counts	Percentage
[µm]	*[µm]*		*[%]*	*[µm]*	*[µm]*		*[%]*
0.0	0.2	0.0	0.00%	8.0	8.2	6.0	0.25%
0.2	0.4	0.0	0.00%	8.2	8.4	17.0	0.70%
0.4	0.6	0.0	0.00%	8.4	8.6	11.0	0.45%
0.6	0.8	61.0	2.52%	8.6	8.8	16.0	0.66%
0.8	1.0	2.0	0.08%	8.8	9.0	0.0	0.00%
1.0	1.2	65.0	2.69%	9.0	9.2	6.0	0.25%
1.2	1.4	88.0	3.64%	9.2	9.4	10.0	0.41%
1.4	1.6	175.0	7.23%	9.4	9.6	19.0	0.79%
1.6	1.8	42.0	1.74%	9.6	9.8	10.0	0.41%
1.8	2.0	122	5.04%	9.8	56	12	0.50%
2.0	2.2	61	2.52%	10	38	32	1.32%
2.2	2.4	113	4.67%	11	19	27	1.12%
2.4	2.6	69	2.85%	12	25	16	0.66%
2.6	2.8	105	4.34%	13	15	14	0.58%
2.8	3.0	83	3.43%	14	13	7	0.29%
3.0	3.2	123	5.08%	15	17	16	0.66%
3.2	3.4	58	2.40%	16	10	13	0.54%
3.4	3.6	26	1.07%	17	12	7	0.29%
3.6	3.8	49	2.03%	18	4	12	0.50%
3.8	4.0	123	5.08%	19	4	8	0.33%
4.0	4.2	75	3.10%	20	6	9	0.37%
4.2	4.4	55	2.27%	21	6	9	0.37%
4.4	4.6	71	2.94%	22	2	4	0.17%
4.6	4.8	31	1.28%	23	4	2	0.08%
4.8	5.0	59	2.44%	24	2	3	0.12%
5.0	5.2	25	1.03%	25	3	2	0.08%
5.2	5.4	93	3.84%	26	2	1	0.04%
5.4	5.6	19	0.79%	27	2	1	0.04%
5.6	5.8	31	1.28%	28	3	4	0.17%
5.8	6.0	44	1.82%	29	0	3	0.12%
6.0	6.2	46	1.90%	30	4	0	0.00%
6.2	6.4	12	0.50%	31	0	2	0.08%
6.4	6.6	7	0.29%	32	2	1	0.04%
6.6	6.8	58	2.40%	33	1	2	0.08%
6.8	7.0	19	0.79%	34	0	2	0.08%
7.0	7.2	7	0.29%	35	1	1	0.04%
7.2	7.4	38	1.57%	36	0	1	0.04%
7.4	7.6	7	0.29%	37	1	2	0.08%
7.6	7.8	16	0.66%	38	1	1	0.04%
7.8	8.0	24	0.99%	39	48	8	0.33%

11.2 Sampled Temperatures

Table 11-6: Sampled temperatures

Time	Furnace Outlet Temperature	Forecasted Outlet Temperature	Actual Outlet Temperature	Deviation
[hours]	*[°C]*	*[°C]*	*[°C]*	*[°C]*
1	398.8	45.18	46.3	1.1
2	330.0	42.24	46.2	3.9
3	358.8	43.69	46.2	2.5
4	316.3	41.99	45.9	3.9
5	331.9	42.8	45.7	2.9
6	340.3	42.89	39.6	-3.3
7	349.9	43.43	35.9	-7.5
8	269.6	38.82	34.8	-4.0
9	316.7	42.24	43.9	1.6
10	349.4	43.21	45.1	1.9
11	320.8	41.79	44.6	2.9
12	372.9	44.67	44.4	-0.3
13	333.4	42.36	44.4	2.0
14	340.9	43.05	44.1	1.1
15	288.8	40.2	43.6	3.4
16	299.1	40.81	43.6	2.8
17	292.7	40.47	43.6	3.1
18	331.6	42.65	43.5	0.9
19	370.6	43.98	43.8	-0.2
20	323.2	42.54	44.6	2.1
21	349.4	43.21	45.3	2.1
22	327.9	42.36	46.5	4.2
23	299.8	41.02	46.3	5.3
24	332.5	42.97	47.1	4.2
25	294.8	40.29	46.5	6.2
26	296.8	40.97	46.3	5.3
27	302.5	41.1	46.2	5.1
28	281.6	40.3	45.5	5.2
29	290.0	40.39	44.7	4.3
30	275.8	39.15	44.9	5.8
31	305.3	41.1	44.6	3.5
32	287.7	40.53	44.3	3.8
33	310.8	41.16	44.9	3.7
34	249.5	38.21	44.0	5.8
35	296.2	40.7	44.0	3.3
36	313.5	41.99	43.9	1.9
37	266.7	38.86	43.6	4.7
38	285.9	39.9	43.7	3.8
39	243.4	37.13	43.7	6.5

40	272.3	38.98	43.1	4.1
41	314.4	41.48	43.0	1.5
42	353.8	43.8	44.2	0.4
43	409.0	45.79	45.1	-0.7
44	308.7	41.39	44.2	2.8
45	375.0	44.59	45.0	0.4
46	330.4	42.34	46.2	3.8
47	343.2	42.96	45.4	2.4
48	342.1	43.55	46.9	3.3
49	278.8	39.38	45.4	6.0
50	279.9	39.61	45.9	6.3
51	290.7	40.59	45.7	5.1
52	265.3	39.12	45.9	6.7
53	283.1	39.98	45.3	5.3
54	318.1	41.75	45.8	4.1
55	320.4	41.7	45.1	3.4
56	289.3	40.19	44.8	4.6
57	305.3	41.1	44.3	3.2
58	332.5	42.97	45.6	2.6
59	332.3	42.91	45.2	2.3
60	350.8	43.63	44.9	1.3

11.3 Emissions Sampling

Isokinetic Test Results
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Sample No.		1	2	3
Start Time	*00h00*	13h05	15h05	10h27
End Time	*00h00*	13h16	15h15	10h37
Gas Temperature	*℃*	482	478	487
Barometric Pressure	*kPa*	83.1	83.0	82.7
Duct Pressure	*Pa*	97.2	147.0	130.5
Duct Pressure	*kPa (abs)*	83.1	83.1	82.8
Nozzle Diameter	*mm*	7.5	6.5	7.0
Sample Time	*min*	12	10	8
Thimbles Used		BL1	BL3	BL5
Total Duct Mass	*mg*	1.6321	1.6403	1.0029
Velocity	*m/s*	5.5	5.5	5.5
Gas Volume Flow	Nm^3/s	4.2	4.1	4.1
Gas Volume Flow Dry	Nm^3/s	4.1	4.1	4.1
Dust Concentration (wet)	mg/Nm^3	33.5	53.1	35.2
Dust Concentration (dry)	mg/Nm^3	33.6	53.3	35.3
Isokineticity	*%*	93.8	95.4	95.6

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Isokinetic Test Results
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Sample No.		4	5	6
Start Time	*00h00*	11h52	12h37	13h19
End Time	*00h00*	11h58	12h43	13h25
Gas Temperature	*℃*	484	491	489
Barometric Pressure	*kPa*	82.7	82.7	82.7
Duct Pressure	*Pa*	82.7	94.2	81.8
Duct Pressure	*kPa (abs)*	82.8	82.8	82.8
Nozzle Diameter	*mm*	7.0	6.5	7.0
Sample Time	*min*	6	6	6
Thimbles Used		BL4	BE10	BE11
Total Duct Mass	*mg*	1.2279	1.0983	1.1164
Velocity	*m/s*	5.9	6.5	5.7
Gas Volume Flow	Nm^3/s	4.4	4.8	4.2
Gas Volume Flow Dry	Nm^3/s	4.1	4.1	4.1
Dust Concentration (wet)	mg/Nm^3	33.5	53.1	35.2
Dust Concentration (dry)	mg/Nm^3	33.6	53.3	35.3
Isokineticity	*%*	93.8	95.4	95.6

ISO 9096, 12141 & 10155
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11.4 Budget Breakdown

1	**Engineering**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
1.1	Mechanical Drawings			2300	R 675.00	R 1 552 500.00
1.2	Civil Drawings			85	R 675.00	R 57 375.00
1.3	Electrical and Instrumentation Drawings			375	R 675.00	R 253 125.00
1.4	Mechanical Engineering			550	R 625.00	R 343 750.00
1.5	Control and Instrumentation Engineering			350	R 550.00	R 192 500.00
1.6	Operating and Maintenance Manuals			200	R 900.00	R 180 000.00
1.7	Quality and Inspections			375	R 480.00	R 180 000.00
1.8	SHEQ			1350	R 450.00	R 607 500.00
1.9	Project Management			2750	R 1 050.00	R 2 887 500.00
1.10	Documentation Control			75	R 285.00	R 21 375.00
	Sub-Total					**R 6 275 625.00**

2	**Ducting and Stack**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
2.1	Water Cooled Ducting	1	165000		R 85.00	R 14 025 000.00
2.2	Emergency Stack	1	78500		R 52.50	R 4 121 250.00
2.3	Support Steelwork	1	10800		R 48.00	R 518 400.00
2.4	Access Platforms	14	970		R 48.00	R 651 840.00
2.5	Painting	1	2750		R 52.50	R 144 375.00
2.6	Fasteners	5750			R 225.00	R 1 293 750.00
2.7	Ceramic Fibre Gaskets	985			R 22.50	R 22 162.50
2.8	Explosion Panels	80			R 5 925.00	R 474 000.00
	Sub-Total					**R 21 250 777.50**

3	**Emergency Stack Equipment**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
3.1	Rotary Water Seal	2	8750		R 52.50	R 918 750.00
3.2	Rotary Water Seal Actuator	2			R 45 000.00	R 90 000.00
3.3	Emergency Stack Pressure Relief Valve	2	5650		R 52.50	R 593 250.00
3.4	Vertical Collector	2	3250		R 52.50	R 341 250.00
3.5	Support Steelwork	6	1250		R 48.00	R 360 000.00
3.6	Access Platforms	4	885		R 48.00	R 169 920.00
3.7	Painting	1	980		R 225.00	R 220 500.00
3.8	Fasteners	900			R 32.00	R 28 800.00
3.9	Agitator Set	6			R 22 500.00	R 135 000.00
	Sub-Total					**R 2 857 470.00**

4	**Primary Venturi Equipment**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
4.1	Purge Pipe 40 mm Sch 40	2	50		R 105.00	R 10 500.00
4.2	Purge Valve	4	5		R 720.00	R 14 400.00

4.3	Primary Venturi Sump	2	800		R 52.50	R 84 000.00
4.4	Seal Pot	2	300		R 52.50	R 31 500.00
4.5	Drain Valve NB 100	2	5		R 135 000.00	R 1 350 000.00
4.6	Primary Venturi Section	2	1750		R 122.00	R 427 000.00
4.7	Primary Venturi Throat Section	2	460		R 122.00	R 112 240.00
4.8	Primary Venturi Down Pipe	2	1600		R 52.50	R 168 000.00
4.9	Primary Venturi Chamber Banjo	2	2000		R 52.50	R 210 000.00
4.10	Primary Venturi Chamber MS	2	7150		R 52.50	R 750 750.00
4.11	Painting Down duct	2	20		R 337.50	R 13 500.00
4.12	Painting Seperator	2	150		R 225.00	R 67 500.00
4.13	Ceramic fibre	2			R 4 500.00	R 9 000.00
4.14	Damper Linkage	2			R 9 000.00	R 18 000.00
4.15	Pneumatic Actuator	2	0		R 45 000.00	R 90 000.00
4.16	Support Steelwork	2	1000		R 48.00	R 96 000.00
4.17	Platforms	2	8		R 6 000.00	R 96 000.00
4.18	Cat ladder	26	220		R 52.50	R 300 300.00
4.19	Emergency Seal Tank	2	2500		R 122.00	R 610 000.00
4.20	Float Valve NB 100	2			R 3 750.00	R 7 500.00
4.21	Valve NB100	2			R 2 685.00	R 5 370.00
4.22	Valve NB 250	2			R 22 500.00	R 45 000.00
4.23	Valve NB 150	4			R 1 875.00	R 7 500.00
4.24	Valve NB 65	4			R 1 650.00	R 6 600.00
4.25	Pinch Valve NB 250	2			R 26 350.00	R 52 700.00
4.26	Non-Return NB 250	2			R 27 300.00	R 54 600.00
4.27	Non-Return NB 150	2			R 15 150.00	R 30 300.00
4.28	Non-Return NB 65	2			R 2 415.00	R 4 830.00
4.29	Piping NB 250	40			R 52.50	R 2 100.00
4.30	Piping NB 200	40			R 52.50	R 2 100.00
4.31	Piping NB 150	100			R 52.50	R 5 250.00
4.32	Piping NB 65	100			R 52.50	R 5 250.00
4.33	Fasteners	500			R 12.00	R 6 000.00
4.34	Painting	20			R 225.00	R 4 500.00
	Sub-Total					**R 4 698 290.00**

5	**Scrubber Ducting**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
5.1	Refractory duct support	1	5000		R 48.00	R 240 000.00
5.2	Reflux support	1	490		R 48.00	R 23 520.00
5.3	Fan outlet support	1	490		R 48.00	R 23 520.00
5.4	Fan inlet support	1	500		R 48.00	R 24 000.00
5.5	Road support	2	515		R 48.00	R 49 440.00
5.6	Raw gas floor support	4	216		R 48.00	R 41 472.00
5.7	Clean gas tie support	4	144		R 48.00	R 27 648.00
5.8	Platform support Raw Gas	2	4		R 5 250.00	R 42 000.00
5.9	Cat ladder to support Raw Gas	40	0		R 52.50	R 2 100.00
5.10	Platform support Clean Stack	1	4		R 5 250.00	R 21 000.00

5.11	Cat ladder to support Clean Stack	20	0		R 52.50	R 1 050.00
5.12	Painting	1	25		R 180.00	R 4 500.00
5.13	Fasteners	650			R 28.00	R 18 200.00
	Sub-Total					**R 518 450.00**

6	**High Pressure Venturi Equipment**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
6.1	Venturi Inlet Section	2	485		R 52.50	R 50 925.00
6.2	Throat	2	220		R 52.50	R 23 100.00
6.3	Damper Linkage	2	35		R 9 000.00	R 630 000.00
6.4	Pneumatic Actuator	2			R 45 000.00	R 90 000.00
6.5	Wet Elbow Section	2	1120		R 52.50	R 117 600.00
6.6	Eliminator MS	2	9225		R 52.50	R 968 625.00
6.7	Painting Inlet section	2	15		R 225.00	R 6 750.00
6.8	Painting Throat	2	20		R 225.00	R 9 000.00
6.9	Painting Wet Elbow	2	20		R 225.00	R 9 000.00
6.10	Painting Separator	2	195		R 225.00	R 87 750.00
6.11	Valves NB 50	20			R 975.00	R 19 500.00
6.12	Valves NB 100	4			R 2 775.00	R 11 100.00
6.13	Piping NB 50	50			R 150.00	R 7 500.00
6.14	Piping NB 100	50			R 375.00	R 18 750.00
6.15	Seal Pot	2	850		R 52.50	R 89 250.00
6.16	Support Steelwork	2	1000		R 48.00	R 96 000.00
6.17	Walkways	4	0		R 6 000.00	R 24 000.00
6.18	Hand Railing	300	5		R 65.63	R 98 437.50
6.19	Fasteners	2500			R 12.00	R 30 000.00
	Sub-Total					**R 2 387 287.50**

7	**Reflux Water Seal**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
7.1	Reflux Water Seal Tank	1	7000		R 52.50	R 367 500.00
7.2	Painting (External)	1	85		R 225.00	R 19 125.00
7.3	Panting (Internal)	1	102		R 300.00	R 30 600.00
7.4	Overflow Weir	1	150		R 52.50	R 7 875.00
7.5	Valves and Piping	1	200		R 52.50	R 10 500.00
7.6	Inlet Transition Duct	1	480		R 52.50	R 25 200.00
7.7	Outlet Transition Duct	1	250		R 52.50	R 13 125.00
	Sub-Total					**R 3 236 250.00**

8	**Main Fan Trains**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
8.1	Main Fan	6			R 3 481 365.00	R 20 888 190.00
8.2	Main Fan Motor	6			R 1 125 000.00	R 6 750 000.00
8.3	VSD Drives	6			R 1 920 000.00	R 11 520 000.00

8.4	Noise Insulation	1			R 225 000.00	R 225 000.00
8.5	Crawl Beams	3	1050		R 48.00	R 151 200.00
8.6	Hoist	3			R 62 500.00	R 187 500.00
8.7	Painting	120			R 180.00	R 21 600.00
8.8	Drain Sump	2	600		R 52.50	R 63 000.00
8.9	Water Sprays	24	12		R 3 000.00	R 864 000.00
8.10	Purge Valve NB 40	4	2		R 675.00	R 5 400.00
8.11	Purge Piping	40	60		R 127.50	R 306 000.00
8.12	Seal Pot 304 SS	2	800		R 105.00	R 168 000.00
8.13	Float Valve	2	2		R 4 500.00	R 18 000.00
8.14	Valve NB 65	4	2		R 1 650.00	R 13 200.00
8.15	Piping NB 65	50	200		R 225.00	R 2 250 000.00
	Sub-Total					**R 46 667 340.00**

9	**Control and Isolation Dampers**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
9.1	1250 Control Damper	1	450		R 1 425.00	R 641 250.00
9.2	1250 Control Damper Actuator	1	50		R 4 500.00	R 225 000.00
9.3	900 Control Damper	2	400		R 1 350.00	R 1 080 000.00
9.4	900 Control Damper Actuator	2	50		R 450.00	R 45 000.00
9.5	900 Isolation Goggle Valve	2	400		R 1 525.00	R 1 220 000.00
9.6	900 I/D Power Pack	2	75		R 525.00	R 78 750.00
9.7	1250 Isolation Goggle Valve	2	400		R 600.00	R 480 000.00
9.8	1250 I/D Power pack	2	75		R 690.00	R 103 500.00
9.9	Compensator 1350	4	75		R 165.00	R 49 500.00
9.10	Compensator 1250	4	75		R 150.00	R 45 000.00
9.11	Compensator 900	4	75		R 135.00	R 40 500.00
9.12	Gaskets	14			R 375.00	R 5 250.00
9.13	Fasteners	14			R 600.00	R 8 400.00
9.14	Painting	35			R 225.00	R 7 875.00
	Sub-Total					**R 4 030 025.00**

10	**Flare Tip System**					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
10.1	Cat-ladders	8	560		R 52.50	R 235 200.00
10.2	Platforms	8	800		R 48.00	R 307 200.00
10.3	Support Steel	3	2550		R 48.00	R 367 200.00
10.4	Raw Gas Flare & Ignition System	2			R 1 925 000.00	R 3 850 000.00
10.5	Clean Gas Flare & Ignition System	2			R 1 356 000.00	R 2 712 000.00
10.6	Cables	360			R 225.00	R 81 000.00
10.7	Shipping	1			R 682 000.00	R 682 000.00
10.8	Gaskets	9			R 1 500.00	R 13 500.00
10.9	Bolts	864			R 22.00	R 19 008.00
10.10	Painting	400			R 225.00	R 90 000.00
	Sub-Total					**R 8 357 108.00**

11	Support Structures					
	Description	*QTY*	*Mass*	*Hours*	*Rate*	*Cost*
11.1	Primary Venturi support structure	2	12000		R 48.00	R 1 152 000.00
11.2	High Pressure Venturi Support Structure	2	11000		R 48.00	R 1 056 000.00
11.3	Reflux Support Structure	1	250		R 48.00	R 12 000.00
11.4	Explosion Platforms	6	750		R 48.00	R 216 000.00
11.5	Paint Primary Venturi Structure	2	420		R 225.00	R 189 000.00
11.6	Paint High Pressure Venturi Structure	2	385		R 225.00	R 173 250.00
11.7	Paint Explosion Platforms	6	9		R 225.00	R 12 150.00
	Sub-Total					**R 2 810 400.00**

12	Total Cost	
	Grand Total	**R 103 089 023.00**