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Waste Heat and Energy Recovery System from Smelter Off-gas for a Platinum Processing Plant

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Abstract

Most mineral processing companies are energy intensive especially if smelting is used in extraction. After processing, the energy is correspondingly dissipated as heat and toxic gases, requiring stringent controls for sustainability and safety. In recent years, Southern Africa has grappled with power shortages resulting in the scaling down of company operations. Increases in manufacturing activities demand for more energy but this has evidently outstripped supply due to the depletion of natural resources. Mineral processing industries are probably the worst affected due to fluctuations in world metal prices. These challenges require sustainable production strategies to remain in business. This research was carried out at a platinum processing company in Zimbabwe which uses smelting in extractive metallurgy, consuming millions of dollars in energy but also dissipating this as heat and furnace exhaust gases. The focus of the research was on finding ways to turn these challenges into opportunities by recovering the heat and using it for other purposes. A waste heat and energy recovery system was designed to work in conjunction with the smelters and electrostatic precipitator. The proposed system is expected to increase furnace efficiency by 8.5% with an anticipated output of 1.033 MW and an overall plant efficiency of 22.7%.

Keywords

Energy, Heat, Recovery, Smelting, Sustainability

1. Introduction

Mineral processing plants that utilize smelting in their extractive metallurgy consume a lot of energy and equally energy in the form of heat and smelter off-gases are emitted as waste in the process. Some of the furnace exhaust gases are toxic and harmful to the environment and operators within these plants. Proper handling and control of the smelter off-gases is critical to ensure that the extraction and disposal conforms to environmental policies governing the communities where the operations are domiciled (Shang & Scott, 2011). The research was carried out at a mineral processing company specializing in the mining and processing of platinum group metals and observations made during the work study revealed that the smelters emit off-gas at temperatures ranging from 350°C – 400°C and in the process a lot of heat energy is lost. In such operations, management and control of the off-gas should be in such a way that any leakages are prevented and that the furnace exhaust gases, mostly the toxic Sulphur Dioxide, SO_2 are properly extracted to avoid any harm to the environment. The company currently uses the Electrostatic Precipitator (ESP) which is constructed from a towering structure several meters above the ground and away from the operations. In recent years there has been growing interest to venture into the recovery of this heat and some of the useful greenhouse gases such as CO_2 that are contained within the off-gas (Shang et al, 2010). The major challenge however has been whether research and investment into such ventures and equipment capable of extracting the useful gases and recover the heat, would be economical. However this interest has also been motivated by the growing need for sustainability in manufacturing and mineral processing industries. The ESP which is commonly employed in such industries for the safe extraction of the harmful gases equally requires investment which could be channeled towards comprehensive equipment that can be used for the double role of extraction and recovery.

The Environmental Management Agency (EMA) of Zimbabwe regulates, sets policy and controls environmental issues in Zimbabwe. According to their air pollution control regulation, SI 72 of 2009, manufacturing and processing companies are taxed on pollution levels they emit where the tax amount depends on the concentration of the emissions and mass flows in their bid to promote the “polluter pays principle” (Environmental Management Agency, 2009). With increases and demands on production that sometimes force companies such as the case study company to work three 8-hours shifts per day, carbon emissions are increasing for smelter processes requiring new or tighter regulations on greenhouse gas emissions. The implementation of a waste heat and energy recovery system will assist in the reduction of carbon dioxide emissions and hence reduce company pollution taxes and ozone depletion. This will also enable the company to remain certified to ISO 14001 for adhering to world environmental standards and maintaining their Environmental Management System (EMS) plans and possibly upgrade these to comply with the new standard; ISO14001:2015. On the other hand, the recovery of energy being lost with the smelter off-gases and reusing it will reduce demand on primary energy for the smelter because more power output can be achieved with the same amount of fuel and hence improvements in energy management and efficiency. The reduction of fuel demand due to reduced electricity consumption also helps to save and preserve the country’s natural resource such as coal which are used for electricity generation. World prices for metals in general have been fluctuating, thus in order for the company to remain afloat and in business, it can adopt ways to reduce operational costs in order to maximize profit through the recovery of energy for reuse, thus reducing the demand for energy as well as reductions in air pollution levels that will also reduce pollution taxes and hence realize increases in profitability. The implementation of such a recovery system will no doubt resolve the perennial problem of load shedding and power cuts to avoid the risk of loss of production. The aim of this research was to design a compact, sustainable and environmentally friendly waste and heat energy recovery system by utilizing the excessive waste heat dissipated with the smelter off-gas, through the use of heat exchangers with targeted conversion efficiency of heat to electrical energy of at least 20% and at least 75% recovery of the off-gas heat.

2. Background and Literature Review

Platinum is extracted from ore that contains a host of other minerals such as copper, gold, cobalt, nickel, palladium, and rhodium, which are commonly referred to as the Platinum Group Metals (PGM) (Zimplats, 2015). These ores contain sulphide which when smelted, produces SO_2 (Ciccone & Storbeck, 1997). Although there are possibilities for carefully extracting the SO_2 and use it in the production of sulphuric acid, it is extremely toxic and handling it will require conformity to stringent environmental regulations, thus investing in such a venture will require expensive state-of-the-art equipment and hence it may not be cost effective. Thus, most companies would find it more rewarding to focus on how to eliminate and minimize the occurrence of such harmful off-gases, hence the use of ESP. As such, industry that normally provides funds for research and development and particularly for provision of relevant solutions to their operational problems, have not found enough motivation to invest in this area. Instead, industry in this regard, has been paying attention to and focusing on eliminating the harmful off-gases in neat and environmentally accepted ways (Hilson, 2003), managing greenhouse gas emissions (Norgate & Haque, 2010), sustainable energy management (Gunson et al, 2010) and life cycle assessments and modelling (Durucan et al, 2006). Waste heat is found in various processes particularly exhaust gases of many industrial processes or flue gas streams of air conditioning units and efforts in recovering and reusing this energy have long been in practice (Laamanen et al, 2014). One of the basic methods for recovery of waste heat was to preheat the incoming gas with the exhaust gas and this has been in practice, commercially and in homes, with such examples as home air conditioners or heaters that are used in motor vehicles, derived from heat generated by running engines. There are several different commercial recovery units for the exchange of energy such as recuperators, regenerators, heat pipe exchangers, thermal wheel or rotary heat exchanger, economizers, and heat pumps (Loganathan & Sivakumar, 2013).

Recuperators consist of metal tubes that carry cold or hot exhaust fluid as a heat exchanger where the exhaust fluid is used to preheat the cold fluid before entering the next processing stage. Regenerators are used in industry to recycle the same stream of energy for use after processing. Heat pipe exchangers are very good thermal conductors because of their ability to exchange heat much more than copper. Heat pipes of this nature are common in renewable energy technologies particularly in evacuated tube collectors and they are also commonly used in space, process or air heating, where waste heat from a process is being conveyed to the surrounding due to its exchange mechanism. The thermal wheel or rotary heat exchanger on the other hand comprises of a circular honeycomb matrix of heat take-in material, which is slowly rotated within the supply and exhaust air streams of an air handling system. In case of economizers in process boilers, waste heat in the exhaust gas is passed through a recuperator that carries the inlet fluid for the boiler and thus decreases thermal energy intake of the inlet fluid and can improve boiler performance up to 6% (Rabah & Barakat, 2001 and GazMetro, 2005). Heat pumps change low temperature waste heat into useful heat by using fluids with low heat of vaporization such as organic fluid and refrigerants. They normally consist of a combination of some of the recovery units such as economizers, recuperators and regenerators. This research focused on recovery of heat energy to electricity thus, use was made of some of these heat recovery systems such as heat pumps, regenerators, economizers and recuperators, which are commonly applied in commercial heat recovery systems.

Heat pumps consist of cycles which include the Steam and Organic Rankine cycles, both of which can be used to recover heat from exhaust gases (Hall et al, 2011). The systems use waste heat boilers to recover heat and then heat steam for the Rankine Cycle. Waste heat boilers for these applications recover the heat contained in flue gas (under atmospheric pressure) leaving combustion to generate saturated or superheated steam, or to produce hot water. In the cycle, heated steam at high pressure is passed through a steam turbine to turn the turbine. The turbine then rotates a generator to produce electricity. The exhaust steam water is cooled to restart the cycle and used to preheat the water fed into the boiler as shown in the established Steam Rankine Cycle (SRC) in Figure 1 (Siemens, 2014).

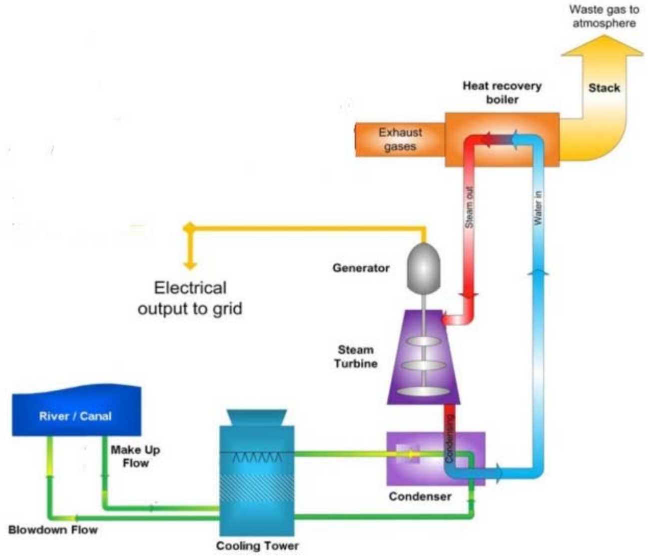
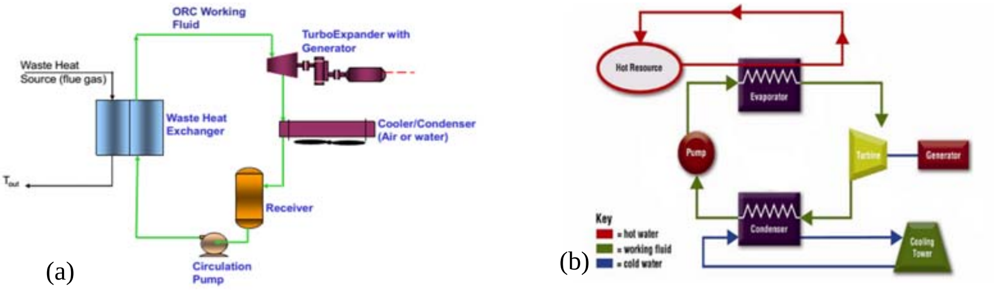


Figure 1. Steam Rankine Cycle in Waste Heat Recovery

This type of cycle was developed and implemented at the mineral processing plant, Tubatse Ferrochrome, in Steelport, South Africa (Els et al, 2013). The Organic Rankine Cycle (ORC) is similar to the SRC but uses low boiling point fluid as the heat transfer medium. This type of cycle makes use of a lower boiling working fluid than a traditional steam boiler, which allows for lower temperature heat recovery. Different working fluids are available for different temperatures; however, at lower temperatures the efficiency is reduced. Heat can be recovered from sources at temperatures as low as 100°C (Safe, 2010). The ORC can be arranged in two ways, either direct or indirect heating. For direct heating, the working fluid directly exchanges heat with the flue gas. This cycle is mostly applied in scenarios where the temperature of the exhaust gas is less than the heat that can break down the working fluid as shown in Figure 2(a), schemed using Microsoft Visio. Indirect heating is almost the same as direct heating except that the working fluid is heated indirectly as shown in Figure 2(b), also schemed using Microsoft Visio. In this process water or thermal oil is used to first recover heat from the exhaust gas and then the recovered heat is used to heat the working fluid.



(a) (b)

Figure 2(a). Direct Heating Organic Rankine Cycle and (b). Indirect Heating Organic Rankine Cycle

Despite the risks involved and the costs required, there has been growing interest to recover heat energy for reuse from smelter off-gas. Due to this interest, researchers and processing companies have devised smart ways to integrate science applications and business models of sustainability for environmentally challenging industries such as in the smelting of PGM ores (Genaidy et al, 2010). Modern smelting processes for ores containing sulphide such as the PGM ore, make use air enriched with oxygen to produce less smelter off-gas but with high levels of SO_2, the concentration of which when combined with moisture in the atmosphere on dissipation from the smelting processes, forms sulphuric acid, in this state commonly referred to as 'acid rain' (Chang et al, 2016). This type of 'rain' has been reported to affect crops, lakes supplying drinking water to communities and even forests, requiring stringent environmental regulations for companies wishing to venture into the handling of smelter off-gas (Kang et al, 2014). Although there are several such techniques available, this review evidently points to challenges of risk and harm to humans as well as costs involved. However, there is still need and it makes business sense to invest in eco-efficiency strategies that can turn such challenges into opportunities. Millions of dollars used to charge the energy required by the smelters every month but probably proportionate amounts could be saved if the heat energy dissipated through the smelter off-gas could be recovered and used for other purposes at the company. This research therefore focused on answering questions revolving around these challenges and how the established technology in heat recovery systems can be combined to extract the off-gas and recover the waste heat, how much of the dissipated heat can be recovered and where it can be reused and whether the proposed venture will be economical to pursue?

3. Research Methodology and Case Study

3.1 Case Study

The research was carried out in 2015 at one of Zimbabwe's platinum mining and processing companies with a special focus on the smelting section of the metallurgical processing plant. The company specializes in the production of the platinum group and other associated metals. Their operations consist of 4 portals (mines), a concentrator and open pit mine while the processing plant, located 70 km away consists of a concentrator and a smelter. These operations are supported by well-equipped engineering design and maintenance departments at both locations. The company also has a very well developed and implemented Business Management System (BMS) with a vision for sustainable growth and development of their manpower for capacity building, hence their keenness to allow access for this research. The world PGM reserves are estimated at 3200 M ounces, with South Africa having 88%, Russia 8%, Zimbabwe 1% and the rest of the world 3% (Johnson Matthey, 2011). Most of the ore undergoes primary crushing at the mines before being transported by road for further processing including smelting, to the metallurgical processing plant. From the observations made during the work study, the smelter appeared to be the consistent bottleneck evidenced by the piling up of ore concentrates delivered either from the concentrator at the mines or from the processing plant. Hence, at the time of carrying out the research, the company was busy planning for the installation of an additional smelter, implying that more energy would be needed and more heat and off-gas will be dissipated. Waste gases dissipated from the smelter have temperatures ranging from 350°C to 1650°C depending on the furnace type (Carbon Trust, 2011). Electric furnaces produce exhaust gases with temperatures ranging between 350°C-450°C as they pass through precipitators and induced drafts fans before being discharged. The amount of heat recovered would depend on the temperature, exhaust gas flow rate and the efficiency of the recovery system. Temperatures around 300°C have the potential to generate 2 MW of electricity (Siemens, 2014), an indication of good potential for recovering heat energy from the smelting processes. The drawings and models in this paper were developed using Microsoft Visio, Microsoft Paint, AutoCAD 2012, AutoCAD Plant 3D or AutoCAD Piping and Instrumentation Design (PI&D) depending on the type and these are annotated in the various sections of this paper.

3.2 Data Collection and Planning

This stage involved gathering all the information necessary in preparation for the design of the waste heat recovery system. The smelting section consists of the Hatch -Elkem furnace and 2 Peirce-Smith converters, in conjunction with the ESP which is installed adjacent to the smelters and converters. The key parameters required to design the waste heat recovery were the minimum and maximum operating temperatures of the furnace and the dissipated smelter off-gas, the flue gas flow rate, dust concentration and operating pressure. This data was collected over a period of 3 months during the work study. The other data which was gathered from the company's records and operating manuals were the inputs such as energy consumption, how much ore concentrate is smelted per day, vis a vis the heat energy generated and dissipated as waste. The basic information pertaining to the smelter section was as follows: Furnace Transformer Rating: 13.5 MW, Primary Voltage: 11 kV, Full Furnace Load: 13.5 MVA, Specific Power Consumption (MWh/t of Concentrates): 1.35

3.3 Design

Using literature and the data collected during the work study, three possible concepts were derived based on the

1. Kalina Cycle, a thermodynamic power cycle that uses an ammonia-water mixture as a working fluid,
2. Thermal oil and ORC where the system indirectly heats the working fluid, usually silicone and thermal oils which are used as the fluid which facilitates heat transfer to the working fluid and,
3. Thermal storage and power generation, which resembles Concept 2 on heat recovery and power generation but additionally the system has an alternative circuit which can store hot oil in the event that the turbine circuit is under maintenance or when preheating air to the gas generator.

The three concepts were compared using the Binary Dominance Matrix and the Kalina Cycle was chosen as the most appropriate concept based on functionality, reliability, ease of manufacture and maintenance, efficiency, ergonomics, quality and cost. The individual components for this concept were then designed and developed further to come up with the waste heat recovery system.

3.4 Modelling and Analysis

The waste heat recovery system, including the recovery mechanism, energy conversion and utilization, was designed based on the Kalina Cycle and incorporated individual designs of the unit's components which comprised, the heat exchanger, piping system and the working fluid (mixture of ammonia and water), economizer, regenerator, evaporator separator, storage tank and the circulating pump. The components were assembled and modelled using AutoCAD Plant 3D from where the required orthographic projections were obtained. For the instrumentation and piping, AutoCAD PI&D was used. Analysis of the design, parameters and equipment used were done to ascertain feasibility, which also included a cost benefit analysis, the basis on which recommendations were made to management of the company.

4. Results and Design

The flue gas source for the PGM smelting process is the 13 MVA Hatch -Elkem furnace and 10' x 15' Peirce-Smith converters. No fuel is burnt in the furnace, hence the volume of waste gas and quantity of flue dust was minimal, such that the bulk of flue gas came from the Peirce-Smith converters. Due to the low volumes of flue gas from the furnace, flue gas properties were thus taken from the converters. The flue gas mainly consisted of SO_2. The exhaust gases were proposed to pass through the economizer.

Table 1. Flue gas Properties

Maximum Temperature	450℃
Minimum Temperature	350 ℃
Dust Concentration	6.8 g/Nm^3
Flue gas flow rate	9.8 Nm^3/s
Pressure	128 kPa

Table 2. Properties of SO_2 at 350 ℃ and 128 kPa

Density	1.5775 kg/m^3
Specific_Heat	774 J/kgK
Compressibility	1.202

Average flow rate, Q_N = 9.8 Nm^3/s at Normal Conditions of 298K (T_N) and 1.013kPa (P_N). Flow rate at operating conditions, Q, 623K (T) and 128 kPa (P) and heat load of off-gas, Q_{source}.

Q = $Q_N \times \frac{T}{TN} \times \frac{PN}{P}$ = 16.2 m^3/s, Mass flow rate $\dot{m}$= Q×ρ = 25.57 Kg/s, $Q_{source} = \dot{m} \times c_p \times \Delta T$ = 4.55MWatts

Due to the dust concentration of 6.8 g/Nm3 in the flue gas, a finned tube heat exchanger was proposed to be used as the economizer as shown in Figure 3, schemed in Microsoft Paint. From standard tables of finned tube exchangers, tube dimensions were taken as Outer diameter, d_o = 20 mm and Inner diameter, d_{in}= 16 mm. Some of detailed component designs were as follows:

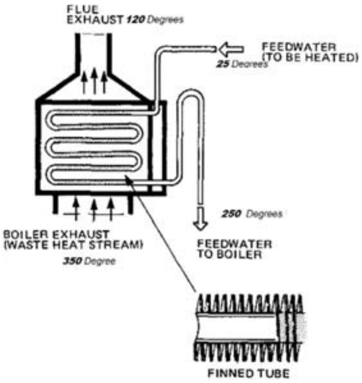


Figure 3. Proposed economizer with finned tube exchangers.

4.1 Pipe Designs

The pipes were designed using carbon steel pipes based on standard pipe sizes according to the American National Standards Institute (ANSI). Optimum diameter, $d_{opt.}$ = $293G^{0.53}\rho^{-0.37}$= 54.81 mm, where G is the mass flow rate. From standard tables for pipe diameters, d = 60.3 mm, with thickness of 1.65mm, d_i = 58.65 mm

Reynolds No., $Re = \frac{4G}{\pi\mu d_i}$ = 114155.8 $>$ 4000 (turbulent flow), Friction factor, f =$1.325(ln(\frac{0.046}{3.7\times d_i} + \frac{5.74}{Re^{0.9}}))^{-2}$ = 0.0213

Pipe head loss due to friction, $h_l = \frac{flv^2}{2gd_i}$ = 0.555 m, Pressure drop,$\Delta P = \frac{4flv^2}{2gd_i}\rho$ = 2.221kPa**,** Pressure head = 0.2264m

Total Head Loss, H = friction head + pressure head + velocity head + valve head + bends head = 5.9742m

Shear force due to turbulent flow, $\tau = f\rho v^2$ = 63.9Pa, Hoop stress for the pipe, $\tau_{hoop} = \frac{Pr}{t}$ = 1.041MPa,

Using the conversion 1-meter head = 9804.139432 Pa, Maximum allowable shear stress of Carbon steel is 200MPa.

4.2 Pump and Motor Selection

For the water alone, volumetric flow rate, Q = 0.00468 m^{3}s^{-1} = 16.85 m^3/hr. Using ANSI tables, the following characteristics of the pump were determined: Impeller diameter = 107 mm, Pump efficiency (μ_p) = 58.3 %, Frequency = 50 Hz, Speed = 2900 rpm, Net Positive Suction Head (NPSH) = 3 m, Motor power = 0.85kW (Break Horse Power, BHP). According to motor selection standards a 1.1 kW motor was selected with an efficiency (μ_m) of 79.2%.

Water horse Power, WHP = 0.641kW, Hydraulic horse Power, ρgQH = 0.274kW,

Overall pump efficiency,$\mu = \mu_p \times \mu_{\mathrm{m}}$ = 46.2%, Pump shaft Power = $\frac{0.274}{0.462}$ k = 0.59kW

For the Ammonia-water mixture, Volumetric flow rate, Q = 0.00853 m^3s^{-1} = 30.708 m^3/hr. Using ANSI tables, the following characteristics of the pump were determined: Impeller diameter = 137 mm, Pump efficiency (μ_p) =64.9%, Frequency = 50 Hz, Speed = 2900 rpm, NPSH = 13.8 m, Motor power = 0.85kW. According to motor selection standards a 2.2 kW motor was selected with an efficiency (μ_{m}) of 82.6%.

Water horse Power, WHP = 1.43kW, Hydraulic horse Power, ρgQH = 0.573kW,

Overall pump unit efficiency, $\mu = \mu_p \times \mu_{\mathrm{m}}$ = 53.6%, Pump shaft Power = $\frac{0.573}{0.536}$ k = 1.1kW

4.3 Water Storage Tank

Design calculations were based on Figure 4, drawn using AutoCAD 2012, a conical bottom of the holding tank, where D = 2m, θ =30°, $d = 0.5$ m

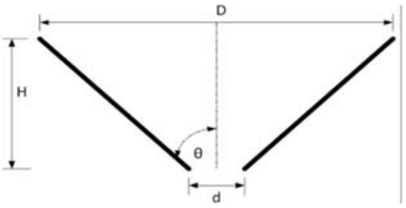


Figure 4. Conical bottom holding tank

$H = \frac{D-d}{2\tan\theta}$ = 1.29903 m, the remaining section of the cone's height was obtained from, $h = \frac{d}{2\tan\theta}$ = 0.43301m

Volume of water contained by the cone, $V = \left(\frac{\pi}{3}R^2H\right) - (\frac{\pi}{3}r^2h) = 1.332\ m^3$

4.4 Ammonia-Water Exchanger

Assuming a 95% efficiency (μ) for the Exchanger, heat transferred to the ammonia-water mixture,

$Q_{\mathrm{w+a}} = \mu \times Q_{\mathrm{w}} = \dot{m} \times c_p \times \Delta T$, Ammonia-water mixture flow rate,$\dot{m}$ = 4.284 Kg/s, Channel velocity = 0.474 ms^{-1}

Reynolds No., $Re = \frac{\rho Vd}{\mu}$ = 1020.153, Nu = 47.21, Plate fin Coefficient, $h_p = \frac{47.21 \times 0.59}{0.006}$ = 4642.32 W/m²°C

Plate pressure drop, $J_f = 0.6(\mathrm{Re})^{-0.3}$ = 0.0751, Path length =1.5m, $\Delta P_p = 8J_f \times \frac{L_p}{d_e} \times \frac{\rho {U_p}^2}{2} = 8473.45$ Pa

Port pressure drop with port diameter of 100 mm, Area = 0.007585 m², Velocity through port, U_{pt} = 1.0867 m/s

$\Delta P_{pt} = \frac{1.3 \times (\rho \times {U_{pt}}^2)}{2} \times N_p$ = 385.5 Pa, Total Pressure Drop = 8.859kPa

Taking the typical plate thickness of 0.75mm, thermal conductivity of Titanium = 21 W/m²°C, Fouling Factor of water = 6000 W/m²°C, Water ammonia-mixture fouling factor = 10000 W/m²°C,

Overall heat transfer coefficient, $U_{overall} = \frac{1}{U_{ovarall}}$ and $U_{ovarall}$ = 1488.12 ≅ 1500 W/m²°C, the initially assumed value.

4.5 Separator Design

Using the Ammonia-water mixture mass flow rate of 4.284 kg/s and assuming this was equivalent to the flow rate of water, $\dot{m}_w$ = 4.283 Kg/s = 15 422.3 Kg/hr, specific volume of water at 550kPa and 120 ℃, V_g = 0.00106013 m^3/kg Density of water at 550kPa and 120℃, ρ_w = 943.281 Kg/m^3. A vertical separator was chosen based on droplet size of less than 100 micron). The design was based on the Souder Brown Equation (Monnery, 2005)

Volumetric flow rate = 16.35 m^3/hr, Velocity = 1.68 ms^{-1}, Ammonia-water mass flow rate $\dot{m}_w = \frac{\dot{m}_v}{x}$, where x = vapour fraction which has not vaporized, Vapour mass flow rate, $\dot{m}_v = \dot{m}_w \times x$ = 1927.8 kg/hr, Density of ammonia vapour at 550kPa and 120℃, ρ_v = 2.92474 kg/m^3, Vapour volumetric flow rate = 659.14 m^3/hr, Velocity = 35.02 ms^{-1}

4.6 Air Cooled Heat Exchanger (ACHE): Forced Draft

The forced draft air cooler was chosen based on the fact that it was not limited to the amount of temperature it can cool and that its mechanical components were easily accessible, which was an advantage for maintenance purposes. After exiting the turbine, the working fluid had 70% ammonia and its cooling temperature at 25℃, which was practically difficult. To raise the cooling temperature, it was mixed with the ammonia-water mixture from the separator to form a mixture with 40% ammonia which enters the condenser at a temperature of around 25℃ and flow rate of 2.41kgs^{-1}. Complete condensation of the 40% ammonia mixture occurred at temperature of 7℃

Expected heat loss = $\dot{m} \times c_p \times \Delta T$ = 273.8kW, assuming a 90% cooling system, the heat required to be absorbed by forced air = 304.2kW = $\dot{m}_a \times c_a \times \Delta T$

The proposed recovery system uses ammonia-water mixture as the working fluid as a direct heating system as shown in the flow on Figure 5, schemed using Microsoft Visio.

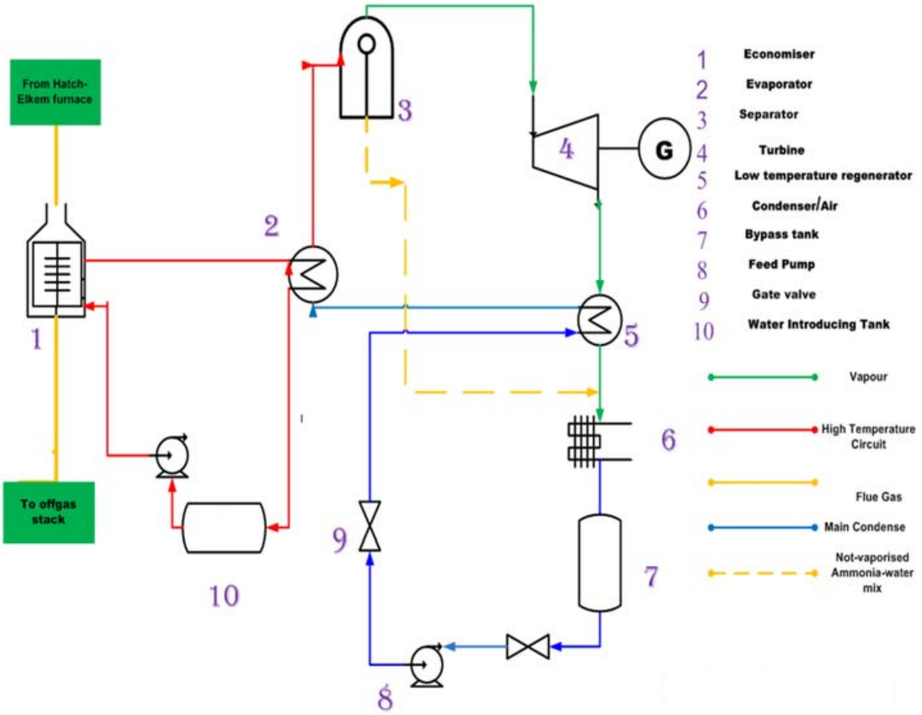


Figure 5. The proposed waste heat recovery system based on the modified Kalina Cycle

4.7 Modelling the Waste Heat Recovery System

The proposed system, based on the designed components, connections and flows were modelled using AutoCAD Plant 3D as well as AutoCAD PI&D showing the link to the Hatch-Elkem Furnace (Smelter) and output through a generator as shown in Figure 6.

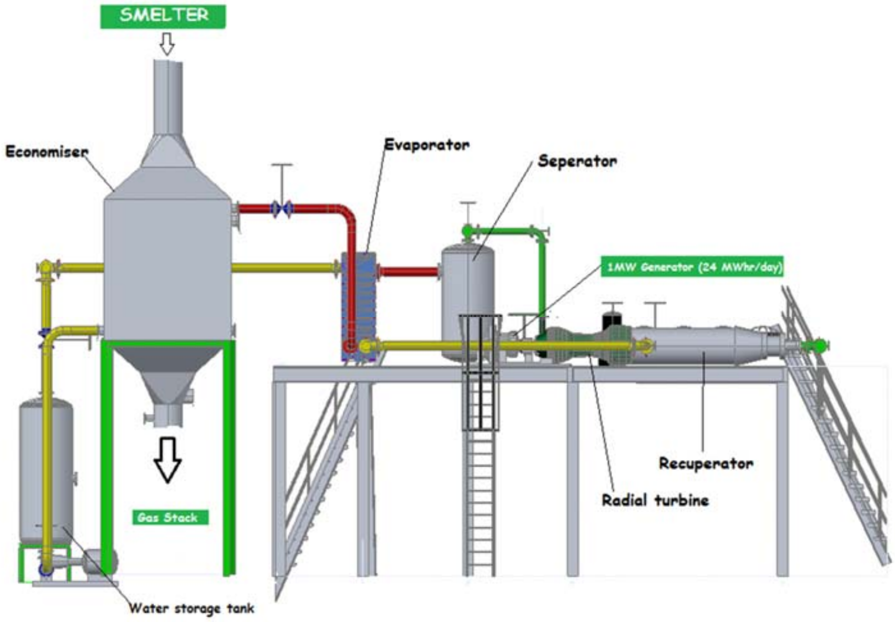


Figure 6. Model of the Proposed Waste Heat Recovery System

4.8 Cost Benefit Analysis

The equipment costs for the major components of the proposed waste heat recovery system are summarized in the bill of quantities in Table 3.

Table 3. Estimated Bill of Quantities for the Waste Heat Recovery System Components

No.	Item	Quantity	Unit Cost ($)	Total Cost($)	Comment
1	Pump	4	700	2,800	Centrifugal
2	Separator	2	30,000	60,000	Vertical
3	Tank	1	1,950	1,950	Buffer Tank
4	Flash Vessel	2	1,000	2,000	Flash Tank
5	Condensate Receiver	2	500	1,000	Buffer Tank
6	Generator	2	50,000	100,000	
7	Radial Turbine	2	100,000	200,000	
8	Finned Tube Economizer	1	23,520	23,520	
9	Gate Valve	16	100	1,600	
10	ACHE	2	10,000	20,000	
11	Plate and Frame Heat Exchanger	2	8,500	17,000	
12	Stainless Steel Pipes	2 x 12m	$10/m	240	1.65 mm thickness
13	Carbon Steel Pipes	2 x 10 m	$4/m	80	1.65 mm thickness
Grand Total				**430,190**	

The parasitic load power was made up of the three power components derived from the water side pump, ammonia-water mixture pump and the air cooled heat exchanger, giving a net output power of 1.033 MW. This can be utilized by the company for Pierce-Smith converters which operate on 250 kW, compressors, pumps or electric motors. The overall plant efficiency was estimated to be:

$$\mu_{overall} = \frac{Net\ OutputPower}{Input\ Power} = \frac{1.033}{4.55} = 22.7\%$$

Table 4. Summary of Anticipated Output

Off gas Gross Power	4.55MWatts
Plant Gross Output Power	1.04MW
Parasite Loads Total Power	6.675kW
Net Output Power	1.033MW
Overall Plant efficiency	22.7%

Table 4 summarises the anticipated output power and overall plant efficiency from the proposed design. The Hatch-Elkem furnace at the company consumes 13.5 MVA and the waste heat recovery system was estimated to produce 1.15 MVA, effectively anticipated to increase the furnace efficiency by 8.52%. The off-gas gross power was anticipated to be 4.55 MW. These calculations implied that the smelter processes were losing approximately 1.033 MJ/s in exhaust gas, translating to 1033 kWh. Using the local tariff of 11 cents per kWh (Kabweza, 2014), this translates to $113.63 per hour worth of energy lost in exhaust gas that can be recovered. Assuming a standard estimate of operation and maintenance costs of 3% of the equipment costs in Table 3, it amounted to $12,905.07, translating to possible yearly savings of $982,493.10. If the company invests in this venture and assuming that the waste heat recovery system yields the anticipated output power, then the company can easily recover their equipment costs in less than a year.

5. Discussion and Recommendations

Three possible concepts were considered for the waste heat energy recovery system based on established principles, namely the Kalina Cycle which utilizes an ammonia-water mixture, thermal oil and ORC where the system heats the working fluid indirectly and thermal storage and power generation. Using the binary dominance matrix and weighted objectives, the Kalina Cycle provided the best solution and was selected as the most optimum concept based on functionality, reliability, ease with which it can be manufactured and maintained, efficiency, ergonomics, quality and cost. This concept was then developed further, component by component, including the incorporation of positive attributes from the other two concepts to develop and propose the waste heat energy recovery system. However, there are a number of limitations that were observed which could be handled by future and further work. To recover the heat energy from such a system, other factors such as flue gas dust rate of deposition should be considered and that in itself may be a complete project. This requires a detailed study on how the exhaust gas heat can be recovered with little or no deposition on the economizer tubes and other associated equipment to ensure long life spans for the chosen components.

Although this will be a very sound investment, further work also needs to be carried out to ascertain functionality by installing a prototype and running it under real time monitoring. The Platinum processing company has been one of the very few companies in Zimbabwe still operating close to 100% capacity utilization owing to its foreign ownership and support it gets from the parent company in terms of expertise, systems and equipment. The company should thus take advantage of this and invest in innovative projects such as the waste heat recovery system in order to remain afloat especially in view of the inconsistent power supplies. There should also be a reliable control system, such as the use of fuzzy logic and programmable logic controllers to monitor and control temperature, pressure and flow rates on entry and exit, particularly for the ammonia-water mixture which should operate below 132^{o}C, and the flue gas ambient temperature after leaving the economizer should always be greater than100^{o}C to avoid formation of water droplets in the flue gas which will increase the load on the induced draft fans. The control mechanism can be programmed to monitor leakages and clogging as well, which may cause heat losses and delay in condensate return, respectively. Inspection and maintenance of heat exchangers and pumping units for fouling and corrosion is recommended to be done regularly, coupled with repair or replacement of seals in the pumping units to minimize water loss by dripping. To attain variable fluid flow, variable speed drives should be utilized on pumping systems to allow pump speed adjustments over a continuous range, thereby improving pump efficiencies and energy savings. Variable speed drives also allow the motor to be started with a lower start up current (usually only about 1.5 times the normal operating current) to reduce wear on the motor and its controller.

6. Conclusions

Mineral processing companies that utilize smelters in their extractive processes not only consume a lot of energy but also dissipate proportionate and corresponding amounts in smelter off-gas and heat. Efforts have been made by many researchers to capture the toxic gases, mainly SO_2 while some researched on how to recover and reuse the heat generated and dissipated by the smelters. Due to the dangers involved and the anticipated costs for the former, focus has been more on the latter. In this research, a waste heat and energy recovery system that consists of thermodynamic equipment such as heat exchangers, economizer, regenerator, evaporator and radial turbine was proposed and designed for use in conjunction with the Hatch-Elkem 13.5 MVA furnace and Pierce-Smith converters at the case study PGM processing company in Zimbabwe. Based on the design and calculations carried out, the anticipated heat energy recovery output was 1.033 MW with an overall plant efficiency of 22.7%, estimated equipment cost of $ 430,190 and a return on investment of 0.438 years, based on the annual energy savings from the recovery. The system is also anticipated to be sustainable and environmentally friendly as there will be no emissions to the atmosphere from the closed loop system. However, further work is required to incorporate control systems to monitor inlet and outlet temperatures, pressure, flow rates and for detecting leakages and clogging.

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