BAYER CALCINATION WASTE HEAT RECOVERY

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Abstract

Alcoa has been investigating methods for reducing energy consumption and, hence, GHG emissions in alumina refining. This paper reports the results of two studies into methods for recovering the energy used in calcination.

The first study considered using low grade waste heat from calcination to drive a power cycle for generating electricity. The Kalina cycle and the Organic Rankine cycle were considered. The study focussed on the Kalina cycle because of its higher efficiency at lower heat source temperatures. A feasibility study was conducted at Alcoa's Jamalco refinery by Siemens & Recurrent Engineering. The findings of the study will be discussed.

The second study developed and evaluated innovative new flowsheets for using low grade waste heat from calcination to evaporate spent liquor. The circuits use readily available process equipment in a configuration not previously utilised (to our knowledge) by the alumina industry. The study showed significant capability to reduce plant steam generation requirements and therefore reduce refinery energy use.

Notation and units

CO_2e	carbon dioxide equivalents
SGA	smelter grade alumina
IPCC	Intergovernmental Panel for Climate Change
GHG	greenhouse gas
USCAP	US Climate Action Partnership
ID fan	induced draft fan
FFE	falling film evaporator
ORC	Organic Rankine cycle

1. Introduction

The weighted average estimate of the energy consumed to produce a tonne of smelter grade alumina (SGA) by the world's alumina refineries is 11.62 GJ/t (IAI, Dec., 2007).

The drivers for reducing energy consumption in alumina operations are well understood and the average energy consumption intensity (i.e. GJ/t alumina) at Alcoa's alumina production operations has decreased by more than 30% since the mid 1960's. Although Alcoa's operations are amongst the most energy efficient in the world, energy still accounts for 20% to 30% of costs providing an economic driver to lower energy usage. Further, Alcoa is strongly committed to reducing this further as part of our greenhouse gas reduction initiatives.

The drivers for reducing GHG emissions and the urgency to align operations with the forecast "carbon constrained" economy of the future are now better understood. These are highlighted in many technical publications on this topic; two notable reports being:

1. The IPCC's[1] 4th Assessment Report on Climate Change (2007), which firmed the scientific basis for human influenced global warming and the projected temperature rise scenarios
2. The Stern Review (2006), which quantified the costs of action & inaction

The total GHG emission from Australia's seven alumina refineries was 13.9 Mt CO_2e in 2006, which equates to an average greenhouse gas intensity of 0.755 t CO_2e/t alumina based on a total Australian 2006 alumina production of 18.4 Mt in 2006 (Australian Aluminium Council). In 2006, Alcoa's direct and indirect CO2e outputs from the Australian alumina refining operations totalled 4.84 Mt, with a GHG intensity of ~0.59 t CO_2e/t alumina (Alcoa in Australia 2006 Sustainability report, 2006).

1 (Intergovernmental Panel for Climate Change, a scientific body established in 1988 by the United Nations Environment Program and the World Meterological Organization)

Despite Alcoa's alumina operations having relatively low GHG intensity, e.g. sinter plants and combination plants powered by coal have GHG intensities that are many times higher, lowering emissions is still a strong area of focus. The drivers include Alcoa's role as a responsible global corporate citizen and the anticipated costs associated with carbon taxes or a carbon trading scheme. The former is an important driver within Alcoa, having been consistently recognised in the Dow Jones Sustainability Index and at World Economic Forum as one of the most sustainable corporations in the world, and as one of the founding members of USCAP[2].

Energy and GHG intensity reductions are being pursued through:

1. productivity improvements
2. efficiency and housekeeping improvements
3. co-generation power
4. technology innovation, and
5. GHG offsets (e.g. Alcoa's 10 million Trees Program to plant 10 million trees worldwide by 2020).

Calciner flue gases release a significant amount of thermal energy to the environment; the output depending on the stack flow, temperature and composition. Typically, stacks release between 1.2 and 1.4 GJ/t of flue gas (datum: 0 °C and 0 kPa). Over 90% of this is associated with the water vapour, mostly as latent heat. The substantial amounts of water vapour present arise from evaporation of residual moisture in the gibbsite cake entering the calciner, the decomposition of the gibbsite to alumina, and from the products of combustion

The amount of thermal energy recoverable depends on the final temperature and the amount of water vapour condensed; for a typical gas fired calciner, it is expected that this can range between 0.1 and 0.8 GJ/t flue gas.

2 US Climate Action Partnership, a group of large businesses and environmental organizations that collectively call upon the US Federal government to urgently enact legislation bringing about significant reductions in GHG emissions

2. Converting Low Grade Waste Heat to Electricity

The problem with using low grade waste heat to generate electricity is that the second law of thermodynamics is against you, i.e. the efficiency is low. The advantage of the organic Rankine power cycle (ORC) over the steam Rankine cycle, used in conventional electrical power generation stations, is that using an appropriate organic working fluid instead of water allows higher power generation efficiencies to be achieved from lower temperature heat sources.

A feature of both the steam Rankine cycle and the ORC is that the boiling and evaporation steps are isothermal. This is a disadvantage in real systems where the heat sources and sinks are finite and the source temperature changes during heat exchange. In this case the actual work delivered by the heat engine is lower than if the working fluid has variable boiling and condensing temperatures and can follow the temperature changes. The reason for the improved efficiency is that minimizing the temperature difference across the evaporation and condenser units reduces the entropy generation in these steps (Figure 1). This concept is very clearly illustrated on a temperature-entropy diagram (Mlcak, 1996; Valdimarsson and Eliasson, 2003) and is the key principle behind the better efficiencies associated with the Kalina power cycle where the working fluid is an NH_3-water mixture.

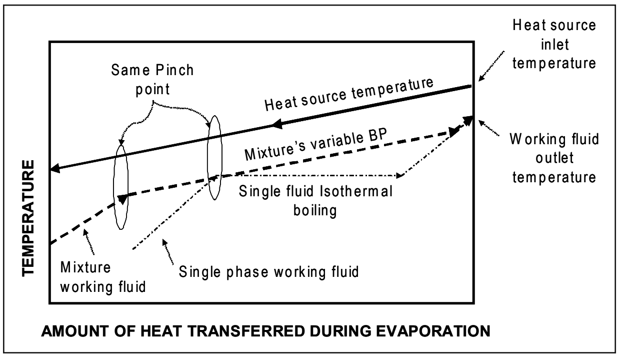

Figure 1. Temperature profiles during heat transfer in the evaporation step of the cycle.

The amount of electricity generated by the Kalina cycle, like all power cycles, will depend on the amount of heat available for the evaporation/boiling step, the grade (temperature) of this heat and the temperature at which the heat can be rejected to the heat sink. Valdimarsson and Eliasson (2003) present a comparison of ORC and Kalina for a geothermal application; their results show that for heat source inlet temperatures in the range 100°C to 150°C the Kalina's power generation is between 15 and 30% higher.

The application of Kalina technology for waste heat recovery was demonstrated in the late 1990's at the DOE's Canoga Park facility in California, by a 3 MWe pilot plant. It was integrated into a combined cycle operation and used high grade waste heat (>500°C). Starting in 1999, the Kalina cycle was used at Sumitomo's Kashima steel works to generate ~3.3 MWe from a low temperature waste heat source (<100°C). They reported 10% generation efficiency and that this was about 40% higher than for an equivalent ORC system. Their heat sink was seawater at 18°C. Sumitomo claimed a saving of 6600 kL of oil over a 4 year period. A number of plants incorporating the Kalina cycle are being built, e.g. Siemens Industrial Solutions & Services have a turn-key order for a 6.4MW facility in Bellheim, Germany.

A simplified schematic flowsheet of the Kalina cycle is shown in Figure 2. It shows another elegant design feature of the circuit, namely, that effectively different working fluids, i.e. with different thermo-physical properties, can be used in different parts of the circuit. The vapour-liquid separator permits high NH_3 concentration mixtures (solid line) to be sent to the waste heat evaporator and low NH_3 concentration mixtures (dashed line) to the recuperator-condenser section. The benefits of this include lower turbine exhaust pressures and lower final working fluid temperatures. For a given combination of available heat source and heat sink there will be optimum NH_3-water compositions. A further design flexibility, available in addition to the variable mixture composition, is the system pressure. The trade-off is between the extra power and cost (Valdimarsson and Eliasson, 2003).

The NH_3-water vapour behaves almost identically to steam because of the similarity in molecular weight, allowing standard steam turbine components to be used. Exotic materials are not required for NH_3-water mixtures but copper alloys must be avoided and, although not familiar to alumina production operations, this is a very widely used chemical system with commercial applications ranging from leaching in the minerals industry to refrigeration plants. Although anhydrous NH_3 is classified as hazardous, aqueous NH_3 is not and is considered an ecologically safe material when handled correctly (Mlcak, 1996).

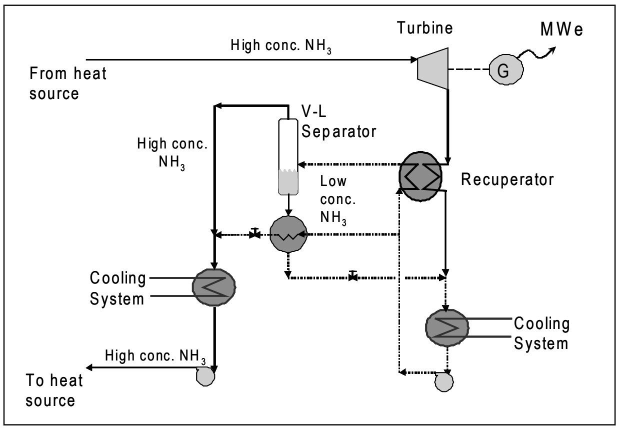

Figure 2. Simplified schematic for the Kalina cycle for low temperature applications.

There are a range of designs for the Kalina cycle, depending on the application. The system evaluated in the Jamalco plant feasibility study was the KCS1-2, from the family of low temperature applications. The feasibility study was conducted by Siemens Industrial Solutions & Services in partnership with Recurrent Engineering, the licensee for Kalina Cycle Power. The heat recovery configuration considered for the Jamalco study is shown in Figure 3. Heat is recovered from alumina coolers and a calciner stack gas. The working fluid is first preheated through one of the coolers, then split and processed in parallel between the waste heat boiler on the calciner stack gas and a second alumina cooler. The two streams are combined and passed through the third alumina cooler, which then feeds the superheated vapour to the turbine.

Two cases were evaluated: one with the current Jamalco arrangement of oil fired calcination and the second assuming gas fired calcination. The first case study indicated that 2.3 MWe could be recovered for operation at name plate capacity. The stack gas temperature was lowered to 135°C to avoid problems with plume dispersal and sulphuric acid condensation. Alumina was assumed to be cooled to 50°C. The second case study indicated higher power generation at 2.7 MWe but a lower cycle efficiency. The main reason for this is that the flue gas temperature could be lowered below the sulphuric acid dew point without the same corrosion concerns. A dedicated cooling system using cooling towers was assumed with an average wet bulb temperature of 24 °C.

A follow-up analysis suggested that the available waste heat is likely to be lower than used in the feasibility study and hence the achievable power generation is expected to be lower. Other important technical issues that still remain involve the integration of this energy recovery technology within Bayer plants, namely:

- Achieving required heat transfer with the current alumina cooler arrangement
- Design and operation of the waste heat boiler, in particular heat transfer surface fouling
- Backup heat removal system for calciners for cases when Kalina plant is down
- Handling any NH_3 leaks.

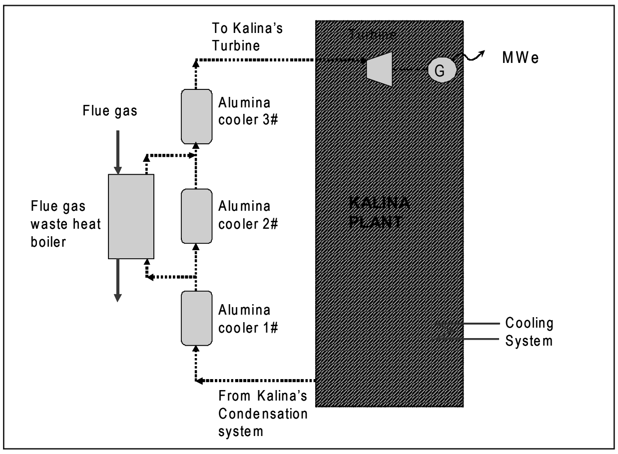

Figure 3. Heat recovery configurations studies at Alcoa's Jamalco Refinery

3. Calciner Waste Heat to Evaporate Spent Liquor

Calciner flue gases contain between 35% and 48% water (by wt%), with significant potential for latent heat and water recovery. A flowsheet for a new concept being developed by Alcoa is shown in Figure 4. If successful, this new process will recover some of this latent heat, together with some sensible heat, and water. The concept involves the transfer of latent and sensible heat from the humid flue gas into a circulating fluid stream (water) in a contacting tower. The hot water from the tower is then sent to the shell-side of an evaporator and used to evaporate spent liquor. The cooled water leaving the shell-side of the evaporator is returned to the tower after a portion is bled off for recovery.

Three designs are being considered for the contacting tower: a packed tower, a tray tower and a Turboscrubber®. The Turboscrubber® is a patented fluidized bed scrubber. A feature of this design is that it allows for higher gas and liquor flow rates, and has higher mass and energy transfer rates. As a consequence, the dimensions of the Turboscrubber should be smaller than the packed and tray towers for the same application, however, the pressure drops will be higher. Figure 5 shows a photo of a pilot scale Turboscrubber at Alcoa and an impingement tray from a tray tower. A pilot investigation is a critical aspect of the development of the new process because of the uncertainty of long term operation in the high dust load gas/vapour stream. Fouling resistance is a key requirement for the process.

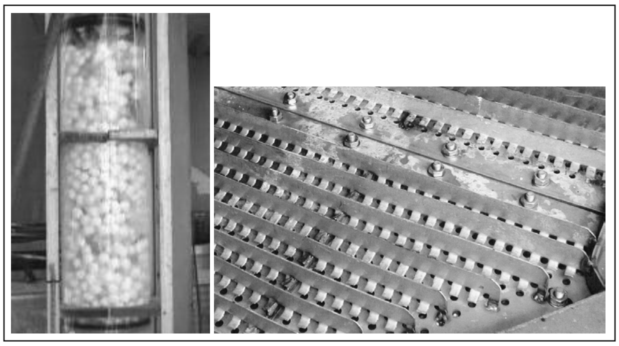

Figure 5. (a) Pilot scale Turboscrubber and (b) impingement tray for tray tower (Lisbon Engineering, with permission).

The quench reduces the temperature to below 100°C and increases the moisture content of the gas feed to the tower and is an in-duct spray. The exhaust gas from the tower needs to be heated to ensure acceptable dispersion from the stack. The options considered for this include a gas fired duct burner or heat exchange using waste heat from the process, e.g. from the alumina coolers. There are pros and cons for both options; the optimum will be site specific. An ID fan is needed to transfer the exhaust gas from the contact tower through to the burner to the stack. Based on the flowsheet to treat 200 t/h flue gas, an ID fan with a 270kW drive and delivering 5 kPa should be adequate.

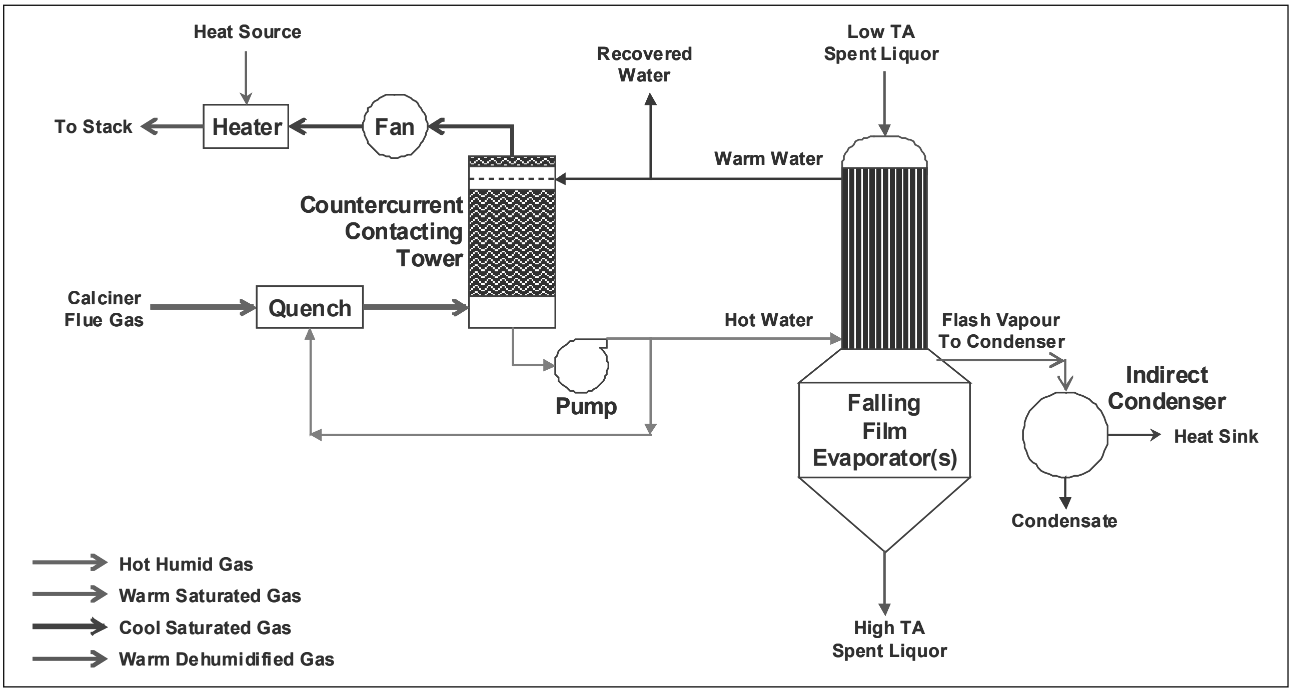

Figure 4. A flowsheet for the recovery of waste heat and water from calciner flue gas.

The flowsheet was modelled using a combination of in-house models tuned to existing Bayer unit operation data and experience, an extensive database of Bayer properties and thermodynamic data and flowsheet models built within ASPEN Plus™ (ASPEN Technology Inc. process simulation software) with state-of-the-art physical properties packages, including added Bayer process properties and unit operations models built in-house.

The flowsheet model included low temperature falling film evaporators (FFE), however, other types of evaporation technology may be used, e.g. forced circulation and rising film evaporators. Based on a 202 t/h flue gas flow at 165 °C, this arrangement is estimated to deliver about 70 t/h of spent liquor evaporation. However, the heat recovery process consumes energy for the blower, pumping liquids and reheating the exhaust gas. The net energy benefit to the plant will range from 0.15 to 0.35 GJ/t SGA; it depends on factors such as the efficiency of the plant's power generation, integration into the plant's power-steam balance and amount of fuel needed to reheat the exhaust gas. The pressure drop in the tower is estimated to be in the range from 3 kPa to 5 kPa.

Other benefits include:

- Potential to recover up to 0.5 kL water/t SGA calcined
- Elimination of the visual plume from the calciner stack
- Reduced particulates in the stack emissions
- Reduced VOCs
- Reduced GHG footprint.

The actual CO_2e reduction will depend on the net energy saved, after accounting for energy used within the heat recovery circuit, the generation efficiency of the plant's electrical power and the GHG intensity associated with the energy being saved. The reduction in CO_2e arising from fitting to a large calciner is estimated to be in the range of 10000 to 20000 t CO_2e per year.

The water recovery potential depends on the available heat sink. For sites where water recovery is important and a suitable heat sink is not available, the water recovery can be increased using fin fan condensers with air pre-cooling by adiabatic water evaporation. A flow sheet incorporating this is shown in Figure 6. Also shown on this figure is the use of waste heat from other locations in the plant to boost the temperature of the hot water stream to the evaporators.

Potential operational issues with the process include:

- Odour in the condensate
- Fouling from dust captured in the recirculating water
- Equipment trips
- Coupling of plant evaporation to calciner availability.

4. Conclusions

Two different approaches for recovering calciner waste heat have been evaluated. One involved using a conventional Kalina power cycle to convert the waste heat to electricity. A feasibility study at Alcoa's Jamalco refinery reported power generation capability of 2.3 MW for the condition studied. An alternative case looking at gas-fired calcination suggested 2.7 MWe power could be obtained, however, at a lower efficiency. A follow-up evaluation suggested that the actual available waste heat is lower and the achievable electrical power delivery would also be lower. Other technical issues remain surrounding the integration of this technology into a commercial Bayer plant.

A novel concept for calciner waste heat recovery has been developed. The method involves contacting a recirculating water stream with the flue gas to extract heat, both latent & sensible, and some water. This heated water can then be used to evaporate spent liquor in an evaporator, preferably a falling film type evaporator. The net energy benefit to the plant was estimated to range between 0.15 and 0.35 GJ/t SGA, depending on a number of factors.

Acknowledgements

The authors would like to acknowledge and thank Sharad Sharma and Seemab Islam from Alcoa for there assistance with ASPEN Modelling, Siemens Industrial Solutions & Services and Mark Mirolli of Recurrent Engineering for their contribution to the Jamalco feasibility study, staff at Jamalco and Josue Navarro for contributions to the Kalina study and finally to Pat Atkins for his support and drive for the Kalina study.

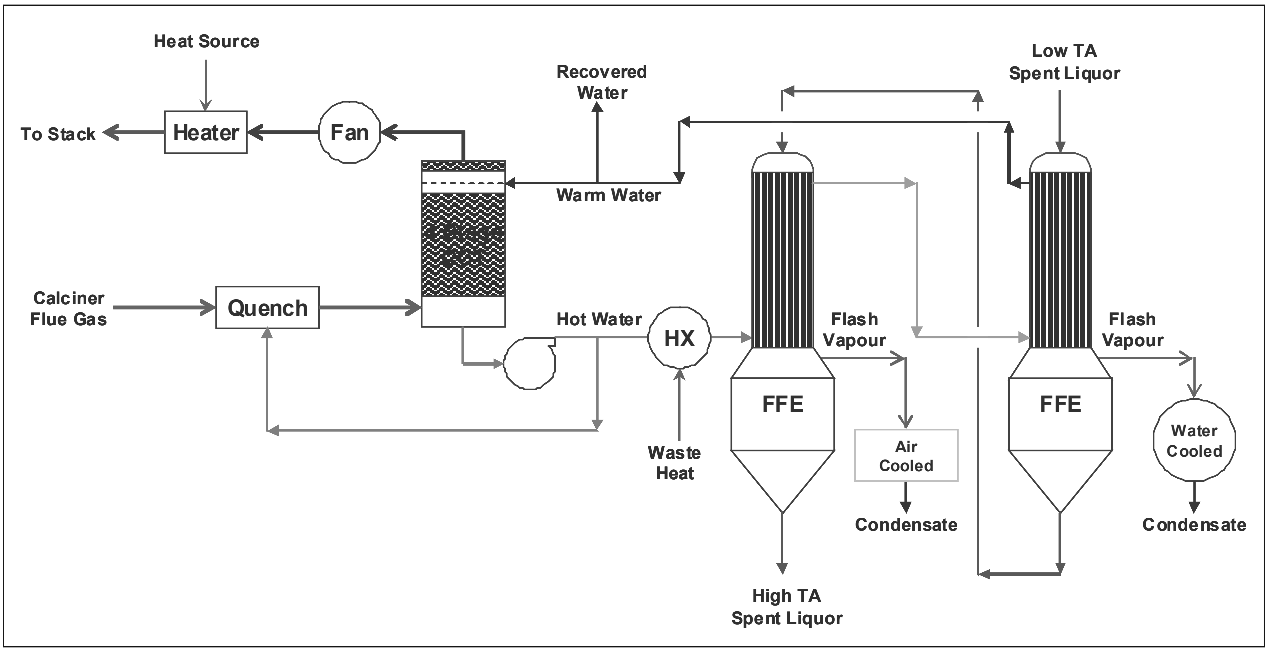

Figure 6. Calciner waste heat recovery with air cooled condensers for greater water recovery.

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