Waste heat to increase energy efficiency in the metals industry

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Energy efficiency improvements achieved using heat recovery processes offer benefits to both the business case and environmental impact of metallurgical facilities.

The US Department of Energy reports that available waste heat sources in industry, which is approximately seven quadrillion BTU (~7400 PJ/y), exceeds the current production of all renewable power sources combined. In Canada there are about 2300Pj/y of available waste heat. Natural Resources Canada (NRCan)[9] has estimated that about 25% of that heat could be recoverable using existing technologies, which in turn, represents a reduction of 27b Mt/y of green house gas (GHG) emissions, plus considerable water savings due to lower water cooling requirements and less fossil fuel consumption.

Recovery of waste heat provides both financial and environmental benefits to process plant operators. The energy that is recovered from these waste heat streams could offer a great opportunity to reduce fuel and energy expenses and greenhouse gas emissions. In summary, waste heat recovery improves the energy efficiency of the heating equipment, lowers operating costs and lowers carbon footprint.

Hatch is engaged in innovative techniques for energy recovery. We systematically identify and quantify waste heat sources, and provide solutions to integrate recovered energy back into the process facility for heat, mechanical work and power generation.

Results include [6]:
- Increased energy efficiency with improved patterns of consumption and reduced energy intensity in industrial processes drawing on secondary sources of heat.
- Replaced and/or reduced the use of other energy sources, consequently lowering operational costs.
- Reduced environmental impact and improved sustainable practices.

Potential heat recovery opportunities

Depending upon the type of process, waste heat can be rejected at virtually any temperature. There are significant opportunities to recover and utilise some of this waste heat as follows:
- As part of a process integration scheme, such as preheating combustion air, drying of materials, etc.
- For heat and/or mechanical power production.
- For electrical power production.

Quality of heat is one of the key elements to consider when analysing the potential of waste heat sources. High grade heat refers to a heat source of 600°C and over. Medium grade heat refers to a heat source of 200°C to 600°C. Low grade heat has a temperature range of below 200°C. Generally, the higher the temperature, the greater the potential value for heat recovery.

This study analyses heat recovery in different metallurgical processes to produce electrical power as follows:
- High to medium grade heat: Using a waste heat boiler (WHB) and steam turbine system.
- Medium to Low grade heat: Using an Organic Rankine Cycle (ORC) system.

In the case of low grade heat sources, an ORC can be used to produce electricity. The cycle is well adapted to low and moderate temperature heat sources such as waste heat from exhaust streams, cooling and condensers. An organic fluid, instead of water, is used as a working fluid. At the lower temperature range the organic fluid has advantages over steam.

Technical comparison

For some applications, gas composition could be an issue for direct gas recycling. In the metallurgical industry, waste gas streams can have a high dust load and/or high temperature that can cause abrasion and thermal stresses. Moisture and SO2/ SO3 in the waste gas may condense in the system, causing corrosion or plugging. In these cases, special materials of construction and design techniques may be required.

There are various commercially available equipment that can effectively be used to produce steam to be used in a steam turbine to produce electricity.
to recover heat from waste heat sources depending on the process, flow rate, chemical and mechanical compositions of the stream and heat quality.

Waste heat boiler and steam turbine generator

Waste heat boilers (WHB) are used in many metallurgical facilities to cool off gases and generate steam. Boiler arrangements can include horizontal or vertical radiation and convection sections, depending on the specific gas characteristics, layout constraints and required outlet temperatures. The steam produced by the WHB can be used to produce electricity via a steam turbine generator. This system follows the Rankine Cycle principles based on steam, which becomes inefficient for electrical power generation using low grade heat, usually below 350°C. At these conditions, the steam produced is at low pressures.

Organic Rankine Cycle (ORC)

Organic Rankine Cycle has the same fundamental principle as the Rankine cycle. However, the difference between the processes is that ORC uses an organic working fluid such as ammonia, hydrocarbons such as iso-pentane, iso-octane, toluene or silicon oil, etc., instead of water. The ORC is a closed cycle process of organic fluid connected to a heat exchanger, which acts as a boiler. ORC has high operational availability, good partial load behavior, quiet operation, allows for unmanned operation with minimum maintenance. ORC is a technologically interesting solution for decentralised applications. It has demonstrated advantages since it provides low environmental impact, low footprint, low operating and maintenance cost, is suitable for remote operation and low heat grade sources.

The organic fluid allows efficient use of waste heat with temperatures and pressures much closer to conventional heating and refrigeration appliances, (e.g. warm water over 90°C and saturated water steam with low/medium pressure). This characteristic benefits the application of low grade hot streams from waste heat sources.

Applications

When recovering thermal losses from equipment it is vital to ensure that the heat recovery does not impact the availability of the equipment. Even very small impacts in plant availability can negate all benefits of heat recovery. The systems should be designed with back-up systems to ensure that outages of the heat recovery system do not require stoppages to the core process equipment. In general, the design of heat recovery systems is significantly easier during the initial development of the plant rather than as retro-fits to the existing equipment. During analysis, there are three key elements to consider:

- Quality, quantity and availability of the heat source. These parameters will define the technology to use.
- Economic impact on the plant, taking into consideration, capital costs, operational costs, including maintenance, additional personnel that might be required as well as the impact on the existing plant.
- Environmental impact, which will take into consideration the footprint of the emissions that, might be avoided by displacing either fossil fuels and/or electricity. For plants located in developing nations the clean development mechanism (CDM) might offer additional economic incentives before and during the lifetime of the project.

Heat losses from laterite nickel production

The smelting of nickel laterites consumes a significant amount of energy, primarily fossil fuel for drying and calcining, and electric power for melting and refining. Waste-gas heat losses are unavoidable in the operation of the nickel process heating equipment such as furnaces, kilns, and dryers. A laterite nickel electric furnace is the main energy consumer and biggest waste heat producer in the process, see Table 1, which refers to a 58 000 tpa ferronickel application.

Laterite nickel process: Waste heat from tapped slag

From laterite nickel production, the majority of the process energy inputs accumulate in the hot slag tapped from the electric furnaces, which accounts for approximately 80% of the total sensible outputs from a furnace. The temperature of slag is approximately 1550 – 1650°C when it exits the furnace.

In most operations, slag is either allowed to cool in large open slag pits or is granulated using water. In the case of wet granulation, a very low grade heat is produced and has minimal potential for heat recovery and reuse. On the other hand, dry granulation of slag, which allows recycling of the slag which can be used as cement aggregate, has attracted considerable interest. Another benefit of dry granulation is its potential for slag heat recovery.

When the slag is granulated, FeO is oxidized to the more stable form, Fe₂O₃.

A commercial operation, shown in Fig.1, commissioned in 1981 and operated for about 10 years during the 1980s and early 90s by Fukuyama Steel Works in Japan, utilised blast granulation and a boiler to produce steam. Although the operation was discontinued and dismantled following the return of low fuel prices in the late 80s, it achieved slag rates of up to 80 t per hour. The total heat recovery was reported to be 80% of the total slag thermal energy.

Recovery of the waste heat is considered to give its main advantages if done during dry granulation, which will avoid water usage, further drying of the product and energy recovery as power. A WHB is proposed to recover about 80% of the available heat. The potential power output is about 20 MW (see Table 5).

Laterite nickel process: Waste heat from off gas

In rotary dryers and kilns, air and fuel are mixed and burned to generate heat, and a portion of this heat is transferred to the heating device and its load. When the energy transfer reaches its practical limit, the spent combustion gases are exhausted from the equipment via an off-gas duct. At this point, the exhaust gases still hold considerable thermal energy, up to 80% of the input energy.

Based on Hatch’s previous studies for the nickel laterite processes [7], the

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Temperature (°C)</th>
<th>Flow rate (Nm³/h)</th>
<th>Available thermal energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag</td>
<td>−1 600</td>
<td>−1 400</td>
<td>98</td>
</tr>
<tr>
<td>Off Gas</td>
<td>−1 000</td>
<td>45 000</td>
<td>20</td>
</tr>
<tr>
<td>Equipment *</td>
<td>−3 200</td>
<td>n/a</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1. Most relevant heat source in a Laterite nickel production.

Notes: * Temperature of the thermal oil proposed for cooling and heat recovery.

<table>
<thead>
<tr>
<th>Systems</th>
<th>Electrical energy consumption (MW)</th>
<th>Gas temperature (°C)</th>
<th>Off gas flow rate (Nm³/h)</th>
<th>Off gas thermal energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace off gas</td>
<td>80</td>
<td>1 000</td>
<td>45 000</td>
<td>20</td>
</tr>
<tr>
<td>Klin off gas</td>
<td>95</td>
<td>&lt;2 500</td>
<td>250 000</td>
<td>23</td>
</tr>
<tr>
<td>Dryer off gas</td>
<td>45</td>
<td>&lt;1 500</td>
<td>50 000</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2. Off gas heat available.
general conditions of the off-gas from the processes are as given in Table 2. 

Major considerations in the design of off-gas system from the furnace could be:

- **Furnace off-gas**: handling of significant amounts of evolved carbon monoxide gas, there are about 20 MW available in this stream. This heat could be recovered using a WHB and steam turbine generator (see Table 5).

- **Klin off-gas**: kiln off-gas generally has a high percentage of water vapour and some SO₂. This combination points to a low acid dew point and indicates that acid condensation will occur, when certain conditions are met. At the temperature below the acid dew point, acid can condense onto contacted ductwork and equipment, causing corrosion. Due to the lower temperature of this heat source, ORC should be considered to produce power.

### Laterite nickel process: waste heat from equipment

Thermal heat losses can be significant from the major equipment in the processing plants. These losses can be generally grouped into the following categories:

- **Losses from the external walls of refractory lined vessels**
- **Radiation losses from openings, hot exposed parts**
- **Heat carried by the cold air infiltration into the furnace**
- **Heat carried by the excess air used in the burners**

Typically, the most significant loss is through the refractory lined walls. Steps should always be taken to minimize the losses from radiation and the losses from excess air. Heat loss due to air infiltration can potentially be recovered in the off-gas if it cannot be prevented.

However, when recovering thermal losses from equipment, especially with the retrofit situation, it is very important to ensure that the heat recovery does not impact the availability of the equipment or process.

From Table 3, heat losses from the dryer and kiln feeding a typical 80 MW furnace can be 1.5 MW and 6.5 MW respectively. The thermal losses from these pieces of equipment occur in the form of natural convection and radiation through naturally cooled steel shells. Unfortunately, the recovery of this energy is difficult due to its low grade quality and its diffusion over a large surface area. The equipment, with the current technology, is insulated as much as possible with low conductivity refractory to reduce these losses.

Heat losses from electric furnaces are generally through the roof and sidewalls. This energy is a typically steady thermal source and is often captured as low grade heat in furnace cooling water and could be recovered at higher temperatures using a thermal oil heat exchanger. Hot thermal oil would then power an ORC to generate electricity at between 12 and 15% thermal efficiency.

Available heat captured from a furnace cooling system also presents a potential heat recovery case. While water is the most common cooling fluid, there are many precedents where thermal fluids have been used where ambient temperatures are very cold and therefore require special fluids to prevent freezing.

The flow of heat through the wall begins in the molten slag bath (1450°C) where convective heat transfer between the bulk temperature of the bath and the frozen face of the refractory wall. Thermal energy is transmitted via conduction through the wall an into furnace cooling elements which are required to remove the intense process heat flux. Finally the heat is transferred into the bulk cooling fluid, water or thermal fluid, through convection at the surface of the cooling passages.

If water is used, water would exit the system with temperature of 50 – 60°C. This heat will be lost in the cooling water tower. However, if thermal fluid, such as thermal oil, is used instead of water, the exiting bulk temperature of the thermal oil could be as high as 200°C, which then could be used to generate electricity in ORC. This application could reduce the plant’s overall water requirement and water treatment while producing power from waste heat (see Table 6).

### Heat losses from aluminium production

Aluminium is produced from alumina by an electrolytic process that uses large quantities of electrical energy to separate aluminium from oxygen in the alumina. In order to smelt alumina into aluminium, alumina is dissolved in a fluorine bath, and electrically reduced to aluminium using a carbon-based anode. The process is relatively intensive in electricity demand and much of the energy is lost as heat.

Sources of waste heat from aluminium production and related processes could be as follows:

- **Off gas from smelter, low grade heat**

### Heat source Temperature °C Available Thermal Energy (MW)

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Temperature °C</th>
<th>Available Thermal Energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roaster off Gas</td>
<td>480</td>
<td>4.4</td>
</tr>
<tr>
<td>Stack Gases</td>
<td>360</td>
<td>5.2</td>
</tr>
<tr>
<td>Calcine Product</td>
<td>550</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4. Most relevant heat sources in a gold roaster process.

Even though the main sources of waste heat at a roaster area of a gold process operation are located in the roaster off-gas, stack gases, the biggest single heat source is the calcine product, which contains about 50 MW thermal energy available per roaster. There are two (2) roasters in the case study implying a total of 100 MW of heat wasted. For the purpose of this study, only the heat available in the calcine product will be considered. The chemical composition of the heat source limits its potential heat recovery and allows for about 60% potential recovery leaving some heat in the off gas to prevent acid condensation. Based on the temperature and flow rate of the process, a fluid bed heat exchanger, similar to a WHB, is proposed to recover the heat and produce steam to drive a steam turbine generator. The results in Table 5 show that about 19 MW of electrical power could...
be produced by using the proper heat recovery strategy.

Platinum group metal (PGM) smelting [5]

Platinum group metal (PGM) is a family of six grayish to silver-white metals with close chemical and physical affinities. Operation processes for PGM consist of concentration (milling, flotation and drying), smelter operation and refineries, base metals refinery (BMR) and precious metals refinery (PMR).

The main energy losses are heat in the cooling system, losses directly from the furnace and heat lost by the furnace off-gas.

Even though, waste heat availability is likely variable on an hourly, daily and weekly basis, waste heat available from the cooling system of the converting process could be a candidate for waste heat recovery application. The converting process is an exothermic process that produces a high temperature off-gas of approximately 1200°C. This gas is currently cooled directly in a water-cooled uptake and then by evaporative spray cooling and quenching. High temperature and pressure cooling water (250°C and 50 bars) from this cooling system is a result from the process and is generally flashed and quenched before drained. This cooling water presents a good waste heat source, which could be recovered to produce electricity using an ORC system.

Results

The results given in Tables 5 and 6 summarise the findings from various case studies completed by Hatch for different global clients. It should be noted that the purpose of the study was to present a comparison between current operating scenarios and potential to utilize the available heat sources to produce electricity only. It is recommended that each opportunity be analysed on a case by case basis to determine which recovery strategy will be most suited for each plant, for their unique operational scenarios.

Assumptions

To provide a common basis for comparison the following are the assumptions used for the studies:

- Fossil fuel displaced is natural gas, in the case of any other fossil fuel utilised a proper analysis should be performed and the CO2 emissions avoided will vary.
- Cost of electricity at $US0,09/kWh,
- Recovery of available heat 70%, due to losses from equipment, transportation, limitations to remove heat from main process, etc. Any improvement in the recovery process will benefit the final output.
- Efficiency of each cycle was assumed at standard ranges: Rankine Cycle: 32%, Organic Rankine Cycle: 8%.

These results provide a starting point for evaluation of these and other operations in the metallurgical industry to help reduce the energy intensity of these operations and their GHG impact. Energy recovery in general, is an important area that needs improvement and these results show that there are areas where the implementation of existing and proven technologies could be of great interest.

References


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### Table 5: Potential results: Application of a Rankine Cycle to recover heat to produce electrical power.

<table>
<thead>
<tr>
<th>Process</th>
<th>Annual metal production</th>
<th>Waste heat source</th>
<th>Temperature</th>
<th>Energy available</th>
<th>Energy recovered</th>
<th>Electrical output</th>
<th>Emissions avoided</th>
<th>Savings (power displaced)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/y</td>
<td></td>
<td>°C</td>
<td>GJ/h</td>
<td>GJ/h</td>
<td>MW</td>
<td>tCO₂/y</td>
<td>$-million/y</td>
</tr>
<tr>
<td>Nickel (Laterite process)</td>
<td>58 000</td>
<td>Stag</td>
<td>1650</td>
<td>353</td>
<td>250</td>
<td>22</td>
<td>69 379</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furnace off gas</td>
<td>1000</td>
<td>40</td>
<td>28</td>
<td>2</td>
<td>7849</td>
<td>2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1 000 000</td>
<td>Cast house</td>
<td>1000</td>
<td>126</td>
<td>88</td>
<td>8</td>
<td>29160</td>
<td>6</td>
</tr>
<tr>
<td>Gold</td>
<td>63</td>
<td>Calciner*</td>
<td>550</td>
<td>360</td>
<td>216</td>
<td>19</td>
<td>60 549</td>
<td>12</td>
</tr>
</tbody>
</table>

Notes: * Only 60% of the heat available could be effectively recovered due to chemical composition.

### Table 6: Potential results: Applying an Organic Rankine Cycle to recover heat to produce electrical power.

<table>
<thead>
<tr>
<th>Process</th>
<th>Annual metal production</th>
<th>Waste heat source</th>
<th>Temperature</th>
<th>Energy available</th>
<th>Energy recovered</th>
<th>Electrical output</th>
<th>Emissions avoided</th>
<th>Savings (power displaced)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/y</td>
<td></td>
<td>°C</td>
<td>GJ/h</td>
<td>GJ/h</td>
<td>MW</td>
<td>tCO₂/y</td>
<td>$-million/y</td>
</tr>
<tr>
<td>Nickel (Laterite process)</td>
<td>58 000</td>
<td>Equipment**</td>
<td>200</td>
<td>20</td>
<td>14</td>
<td>0,6</td>
<td>1840</td>
<td>0,4</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1 000 000</td>
<td>Pot line</td>
<td>130</td>
<td>3040</td>
<td>2128</td>
<td>50</td>
<td>158 000</td>
<td>32</td>
</tr>
<tr>
<td>Platinum</td>
<td>33 000</td>
<td>Converting process</td>
<td>250</td>
<td>54</td>
<td>40</td>
<td>0,9</td>
<td>2800</td>
<td>0,6</td>
</tr>
</tbody>
</table>

Notes: ** ORC thermal efficiency calculated at 15% since the thermal oil is the starting point of reference.