Waste Heat Recovery Valorization with ORC Technology

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INTRODUCTION

The Iron & Steel industry is continuously making progress in energy efficiency and sustainability, improving existing operations and developing novel processes with inherent lower emissions. European Steelmakers are strongly engaged to lower emissions of their existing plants, but there is a consensus that these improvements are not sufficient to achieve the drastic reduction targets set by the European Union. In order to develop breakthrough process solutions and achieve 50% lower emissions in steel production, the major European companies formed in 2004 the consortium ULCOS (Ultra Low CO2 Steelmaking). The ambitious ULCOS work lost momentum in the implementation phase for a series of reasons exacerbated by the financial crisis in 2008. Today, while some of the ULCOS identified processes are under development, the possibility to reduce further EU steel related emissions involves replacing some of the present coal based processes (cok ovens, blast furnaces and steel converters) installing instead new electric steel melting furnaces and natural gas based direct reduction plants. A further increase of EAF steel produced with DRI besides scrap could allow advancing more toward the extremely difficult emission targets set by the EU for the Steel Industry in 2030.

In this scenario, recovering the waste heat generated in Electric Arc Furnaces is a priority goal for steelmakers, in order to improve energy efficiency and sustainability of their primary production processes. Reducing the EAF off gas related losses, typically almost 30% of the energy balance in scrap-based steelmaking, is the first step of an effective heat recovery and valorization effort [1]. The four Turboden ORC (Organic Rankine Cycle) systems now operating or being installed in important EAF steel plants in Europe and Asia demonstrate that ORC is an effective, commercially viable way to valorize the off gas waste heat matching the challenging conditions of EAF steelmaking.

WASTE HEAT VALORIZATION

The first energy saving option is to recover the process waste heat and use it directly as thermal energy. This is often difficult or impractical, due to the large amount of heat available (bigger than any local user), its relative low temperature, the possible mismatch with the user demand when it is variable, the distance or layout constraints to reach a thermal user. When direct use of heat is limited or impossible, the best valorization option is to convert it to mechanical/electrical power typically with a Rankine Cycle. The power produced is only a fraction of the heat available, due to the intrinsic efficiency of the conversion. This efficiency, according to the ideal thermodynamic cycle, is a function of the temperatures of the heat source and of the heat sink.
ORC VS STEAM TURBINE

Traditional Rankine Cycle systems use water and steam as working fluid. They are the common solution for power plants above 10 MW typically with efficiencies above 30% when using superheated steam at high pressure/temperature. Steam turbine Rankine Cycle systems are preferred in large utility size power plants where fuel is the most important cost factor outweighing the higher O&M costs due to steam at high temperature/pressure.

ORC technology, employing high molecular weight working fluids (siloxanes, hydrocarbons and refrigerants) that guarantee dry vapor expansion in every operating condition, is typically preferred for smaller scale power systems up to 10 MW, due to good efficiency, high flexibility and minimum running costs (no dedicated personnel necessary).

The main differences between traditional Rankine Cycle with Steam Turbine and ORC are shown here below (Figure 1).

<table>
<thead>
<tr>
<th>Thermodynamic features</th>
<th>Operation and maintenance costs</th>
<th>Other features</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High enthalpy drop</td>
<td>• Water treatment required</td>
<td>• Common for plants &gt; 10 MWe</td>
</tr>
<tr>
<td>• Superheating needed</td>
<td>• High pressures and temperatures</td>
<td>• Low flexibility</td>
</tr>
<tr>
<td>• Risk of blade erosion</td>
<td>• Specialized personnel necessary</td>
<td>• Lower performance at partial load</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Small enthalpy drop</td>
<td>• Non-oxidizing working fluid with no corrosion issues</td>
<td>• High flexibility and good performances at partial load</td>
</tr>
<tr>
<td>• No need to superheat</td>
<td>• Minimum personnel and O&amp;M</td>
<td>• High availability</td>
</tr>
<tr>
<td>• No risk of blade erosion</td>
<td>• Completely automatic</td>
<td>• Possibility to work at low temperatures (90+°C)</td>
</tr>
</tbody>
</table>

Figure 1. ORC vs Steam turbine

ORC units, after being widely used in distributed generation system with renewables sources (Biomass, Geothermal, Solar), proved to be also effective tools for waste heat valorization in energy intensive industries: oil & gas, cement, glass and more recently steel. The ORC simple, automatic, modulating, fail-safe operation can match the actual primary process regime in all conditions, maintaining the overall system reliability with minimum O&M cost and no additional personnel. These advantages make the ORC a preferable choice in waste heat valorization systems and probably the only practical option when the primary process is highly variable and discontinuous as in scrap based Electric Steelmaking.
ORC SIZE & APPLICATIONS

ORC modules are used for different applications most commonly in sizes up to 10 MW. In case of low temperature sources (around 150°C) such as geothermal applications, ad hoc ORC configurations can extend to 20 MW and above (Figure 2).

![Figure 2. Turboden ORC: size and applications](image)

ORC LINK WITH HEAT SOURCE

When the main heat source is in the gaseous phase (e.g. streams of dust laden EAF exhaust gases), a Heat Carrier loop is typically interposed between the hot source and the ORC (Figure 3).

![Figure 3. Heat recovery scheme with heat carrier](image)

The heat carrier loop allows flexibility in layout and easier decoupling from the primary heat source (e.g. combustion system, main industrial process). In case of highly variable discontinuous heat loads as in EAF Steelmaking, the heat carrier allows to insert a
thermal buffer between the primary heat exchangers and the ORC. When these issues are not critical, the heat carrier may be unnecessary.

Hot Water, Saturated Steam and Thermal Oil are the most common heat carriers used in practice. The choice by the industrial user depends on the specific process considering the site conditions, efficiency, capital cost and ease of operation (Figure 4).

<table>
<thead>
<tr>
<th>Hot Water</th>
<th>Saturated Steam</th>
<th>Thermal Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple technical solution (low temperature, no change of phase)</td>
<td>Medium ORC efficiency (~20% with 27 bar steam)</td>
<td>High ORC efficiency (up to 24% due to high temperature, 310°C)</td>
</tr>
<tr>
<td>Many application in ORC (waste to energy, geothermal plants, etc.)</td>
<td></td>
<td>Reliability (widespread solution in ORC based heat recovery systems)</td>
</tr>
<tr>
<td>Lower ORC efficiency (e.g. 16% with 180°C hot water)</td>
<td>Somewhat complex (e.g. water quality)</td>
<td>Flammable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some operators not familiar with thermal oil</td>
</tr>
</tbody>
</table>

Figure 4. Heat carrier alternatives

Thermal oil, granting higher efficiency, is common in small power plants with biomass combustion and in industrial heat recovery systems (e.g. Cement, Non Ferrous Metals) but seldom found in the steel industry. Saturated steam is preferable when steam can be used at the same site for process/heating or for export to a nearby client.

**TURBODEN ORC PLANTS**

The current fleet of Turboden ORC units, installed or under construction, is summarized in the following table, indicating for each type of application the number of units, size range and the heat carrier employed (Figure 5).

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>SIZE (MW)</th>
<th>PLANTS</th>
<th>HEAT CARRIER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Biomass</td>
<td>0.2 – 8</td>
<td>275</td>
<td>Thermal oil (74) None – Direct exchange (1)</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.5 – 16.5</td>
<td>10</td>
<td>Brine (8) Geothermal water (2)</td>
</tr>
<tr>
<td>Combined Cycle (bottoming of gas turbines or reciprocating engines)</td>
<td>0.5 – 4</td>
<td>12</td>
<td>Thermal oil (9) None – Direct exchange (3)</td>
</tr>
<tr>
<td>Waste to Energy</td>
<td>0.5 – 5.3</td>
<td>9</td>
<td>Thermal oil (7) Pressurized water (1) Saturated steam (1)</td>
</tr>
<tr>
<td>Industrial Heat Recovery (Cement, Glass, Steel, Aluminum, etc.)</td>
<td>0.5 – 5</td>
<td>11</td>
<td>Thermal oil (8) None – Direct exchange (1) Saturated steam (2)</td>
</tr>
<tr>
<td>Solar thermal power</td>
<td>0.6 – 2</td>
<td>3</td>
<td>Thermal oil (3)</td>
</tr>
<tr>
<td><strong>Total Turboden Plants</strong></td>
<td><strong>0.2 – 16.5</strong></td>
<td><strong>320</strong>*</td>
<td><strong>464</strong></td>
</tr>
</tbody>
</table>

* 56 presently under construction included

Figure 5. Turboden ORC plants (update February 2016)
The number of ORCs increased greatly in the last 10 years with many systems in new applications joining the original fleet mostly concentrated in biomass power plants. The size range of the newer ORCs also grew substantially with the more recent applications and with plants in countries where incentives on renewables are absent or smaller.

**ORC IN IRON & STEEL – FROM FOUNDRY CUPOLA TO EAF STEELMAKING**

Back in 1996, Turboden started up an ORC based waste heat valorization system at Fonderia di Torbole a leading European iron foundry supplying the automotive industry. The prototype installation, using the residual heat of a foundry Cupola Furnace exhaust gas conveyed by thermal oil, consisted in fact of two cascaded ORC units. The system operated with one ORC for nearly 10 years producing electricity for the local utility Cogeme. Recently Fonderia di Torbole decided to revamp the plant and to install a new up-to-date Turboden ORC for waste heat valorization at the upgraded Cupola Furnace.

Another ORC application in Steel was in 2011 at the Slab Reheating Furnace of Toscelik Hot Strip Mill in Turkey with multiple small ORCs use hot water as heat carrier [2].

In February 2013, Turboden started up an ORC based waste heat recovery system at NatSteel in Singapore. This is a small direct heat exchange unit (no heat carrier) using the exhaust of the billet reheating furnace at the merchant bar mill of NatSteel, a Tata Steel Enterprise.

Finally and most important, on December 18th 2013 Elbe-Stahlwerke Feralpi GmbH (ESF) started up the world first ORC based waste heat valorization system in Electric Arc Furnace steelmaking in its plant in Riesa (Germany) [3].

This is a more challenging but also more rewarding application due to the nature of the process and the amount of energy involved. Since the EAF off gas stream is discontinuous and highly variable, heat recovery and power production required ad hoc solutions in equipment and controls.

**ORC OPERATION AT ESF STEEL SHOP**

The account of the operating experience at ESF Steelmaking shop, from the original startup in December 2013 to date, testifies the achievement of this innovative ORC application and offers considerations for new projects in EAF and elsewhere [5].

At ESF an EAF off gas iRecovery®¹ system produces nominally 30 t/h of saturated steam with up to 20 t/h conveyed to the 2.7 MW ORC while the rest is delivered to the local utility (Stadtwerke Riesa) for use in the nearby Goodyear Dunlop tire plant.

The ORC reached its nominal power on December 19th, 2013, the second day after start up. More time was then necessary in commissioning with the joint work of ESF, Tenova and Turboden to solve the teething problems of the new installation and to get fully satisfactory performance in continuous operation.

During that period, the ORC fed with 20 t/h of steam at 245°C and 27 bar g demonstrated to exceed by almost 10% the guaranteed power outputs, respectively:

- 2,700 kW gross electric power
- 2,580 kW net electric power

The measuring campaign done at the end of commissioning demonstrated that the overall efficiency of the EAF with the new energy recovery system had increased by 4.5% [4].

After commissioning, the new EAF off gas valorization system has been running continuously following the normal steel shop operating routine practiced at ESF.

After two years from start-up it is worth mentioning significant operating results. In the last 365 days recorded (20.1.2015 to 20.2.2016), steam was available for power production 6,959 hours, the ORC was in parallel 5,783 hours (83.1% availability) producing 12,086,622 kWh (average power 2,090 kW).

The relatively low availability was due to a prolonged shutdown caused by an accident in August 2015 in the medium voltage switchgear.

Aside from that, the ORC availability was in line with typical ORC values. In fact, during the last four months (1.10.2015 to 2.2.2016), the ORC had steam for 2,138 hours, was in parallel 2,045 hours (95.7% availability) producing 4,478,863 kWh (average power 2,190 kW).

The following screenshots of the supervisory PC show the actual operation of the ORC at ESF.

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¹ iRecovery® is the Tenova technology for evaporative cooling and heat recovery in EAF, SAF, BOF and reheating furnaces.
The commercial operation of the ORC based energy recovery system at ESF electric steel plant in Riesa, well demonstrates the ability of the ORC to operate continuously, automatically adjusting to the highly variable EAF working conditions. The European Union recognized the results obtained and the practical experience gained at ESF through the Sustainable Industry Low Carbon scheme. Under this scheme, the project WHAVES (Waste Heat Valorization for more Sustainable Energy Intensive IndustrieS) was launched to disseminate the results obtained and to promote further similar applications [4].

Thanks to ESF hospitality, the innovative EAF waste heat recovery plant in Riesa received visits by many steel mill operators interested to evaluate directly the system features and the actual performance. These visits convinced other steelmakers to follow the route pioneered by ESF installing ORC based systems at their existing EAF steel mills.

ORC AT ORI MARTIN READY TO START UP

A new ORC equipped EAF waste heat valorization system is now in the commissioning phase at ORI Martin steel making plant in Brescia (Figure 7). ORI Martin, leading Italian supplier of engineering steel in bars for the automotive industry and for other mechanical applications is implementing a multimillion Euro energy saving investment in its facilities in Brescia [7].

Fig.6. Screenshots of Turboden ORC at Elbe-Stahlwerke Feralpi EAF
The projects involves a major revamping of the electric steel melt shop with a new improved Consteel®\(^2\), an iRecovery® system producing steam partly exported to local utility A2A to supplement the citywide district heating network and the 1.9 MW Turboden ORC fed with the rest of the steam (Figure 8).

\(^2\) Consteel® is the registered trademark of the Tenova system to continuously pre-heat and feed metallic charge to the EAF.
Like at ESF Riesa, the heat recovery system produces saturated steam, but the pressure and temperature are lower. Differently from ESF there is no radiant heat exchange section close to the EAF. The convection heat exchanger is a horizontal waste heat boiler downstream of the underground, refractory lined, off gas duct bypassing the existing quench tower (Figure 9).

**Consteel EAF with iRecovery® (Tenova)**

**Start-up:** March 2016

- **Summer case:** All steam conveyed to ORC
- **Winter case:** Most steam used for district heating

Steam at ORC inlet: ~ 16 t/h of steam at 15 bar g- 200°C

**ORC gross power:** ~ 1.9 MWe

*The ORC operates with a steam flow rate between 2 and 16 t/h, automatically adapting to the EAF melting cycle.*

Figure 9. EAF Waste Heat valorization at ORI Martin, Brescia, Italy

The new Consteel® EAF was started up in August 2015, the iRecovery® system with convection waste heat boiler was commissioned in January 2106 conveying steam to the A2A heat exchangers for district heating. The ORC, installed in 2015, will start up beginning in March when A2A will reduce the heat demand near the end of the winter heating season.
The new waste heat valorization system at ORI Martin will improve significantly the energy efficiency of steelmaking while maintaining a competitive industrial activity within the city of Brescia. For these reasons the project obtained the support of the European Union Smart Cities program called PITAGORAS, acronym for Promoting Sustainable urban Planning with Innovative and low energy Thermal And power Generation frOm Residual And renewable Sources [8].

NEXT ORC PROJECTS IN IRON&STEEL

In 2015 other prestigious steel companies decided to follow the example of ESF and ORI Martin installing new EAF heat recovery projects in their existing plants. As a result, Turboden will deliver in 2016/2017 two new ORC units for two electric steelmaking plants in Europe and in the Asia. The name of the customers will be disclosed after receiving the corresponding authorization. Counting these two important projects under way, in 2017 six Turboden ORCs are expected to be operating in waste heat valorization in the Iron & Steel industry. The following table summarize these plants and their main features (Figure 11).
CONCLUSION

The experience cumulated in various systems operating in Iron & Steel confirms that ORCs well respond to the steelmakers requirements to have dependable, flexible, easy to run waste heat recovery equipment, guaranteeing significant energy savings with no prejudice to the overall process reliability and no additional personnel.

Two years continuous operation at ESF of the innovative ORC based waste heat valorization system automatically following the highly variable electric furnace process conditions, indicate that ORC deserves being considered best available technology in EAF energy recovery.

The new ORC systems in EAF off gas heat valorization, ready to start up or scheduled for next year, benefit from the feedback of the first projects.

Further improved solutions allow reducing the installed cost per kW of ORC based waste heat recovery systems. This, together with the inherent low O&M costs of the ORC shall encourage other steelmakers to invest in similar energy saving projects.

Additional applications of ORC will likely follow in other Iron & Steel energy intensive processes recovering residual heat, for instance in BOF and in Sinter plants.
REFERENCES


5. A. Foresti, D. Archetti, ORCs in steel and metal making industries: lessons from operating experience and next steps, METEC & 2nd ESTAD, June 2015.

