Energy Efficiency and Clean Energy Usage in Cast House Furnaces

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Abstract

Energy supplies have always been a premium commodity that greatly affect the operating viability of our plants, now more than ever our processes must reduce exposure to the ever-increasing costs associated with energy usage. This is a complicated scenario as we also have a need to use energy more cleanly to comply with the latest environmental legislation. The cast house is no exception to optimised efficiency demands, the big question is, how do we maintain high-performance cast houses while reducing the energy we use and can this be done while respecting a need to reduce the emissions from cast house equipment. In this paper Mechatherm will share its experiences in addressing these issues, including our recent experience in replacing a traditional natural gas combustion system with a hydrogen fuelled burner system. What are the challenges faced in implementing such projects? do the results meet the efficiency and environmental challenge?

Keywords: Energy efficiency, Emissions, Hydrogen Combustion, Cast house, Mechatherm.

1. Introduction

The production of aluminium requires the use of furnaces to convert aluminium into saleable formats. In every stage of this process, whether in refining and re-formatting into specific alloys, re-melting of solid aluminium or reclaiming and recycling scrap aluminium, the act of melting and treating aluminium is made in furnaces of several different types for the various applications associated with our diverse industry. Although these production processes are far less energy intensive than those associated with the extraction of aluminium from bauxite, reducing energy consumption in the cast house area is still a paramount concern; plants need to remain efficient and cost effective and, as an industry, we strive to optimise and prove our credentials as a green industry supporting the world's most recyclable metal.

Our industry faces big challenges ahead, the climate targets set by our governing bodies have become increasingly more ambitious as we try to mitigate against further contributions to climate emissions. The European aluminium industry is responsible for approximately 24 million tonnes of CO_2 equivalent emissions annually [1]. This accounts for about 2.3 % of the global aluminium industry's emissions [1], when considering the aluminium production process.

The industry is actively working towards decarbonisation, with a goal of achieving net-zero emissions by 2050. As an energy-intensive, though highly electrified, and hard-to-abate industry, it is easy to get focused on the reduction areas of plants and this is to a large degree justified; however, in the European arena where we increasingly move towards remelting and recycling, more efficient methods of achieving this must be considered and, given the large number of furnaces used in our industry, any optimisation of energy usage we can adopt will surely have a positive impact on the energy efficiency of our industry. Our challenge is to improve the performance of our cast house furnaces without also making them an energy drain or increasing the pollution contribution of these furnaces.

2. Current Status

Our industry has a core of conventional single chamber reverberatory furnaces that have been using the same basic design for several decades (Figure 1). There are more sophisticated furnaces for dealing with contaminated scrap, but these are not as numerous as the conventional furnaces on which we will focus here.

Figure 1. Typical single chamber furnace.

Unless cleaner forms of heating are available and suitable for the furnace application, such as access to cheap electricity for holding furnace applications, then the furnace will rely on some form of fossil fuel fired burner system for the heat input (Figure 2). A hard-wearing refractory lining is used to thermally insulate the furnace and prevent as much heat loss as possible.

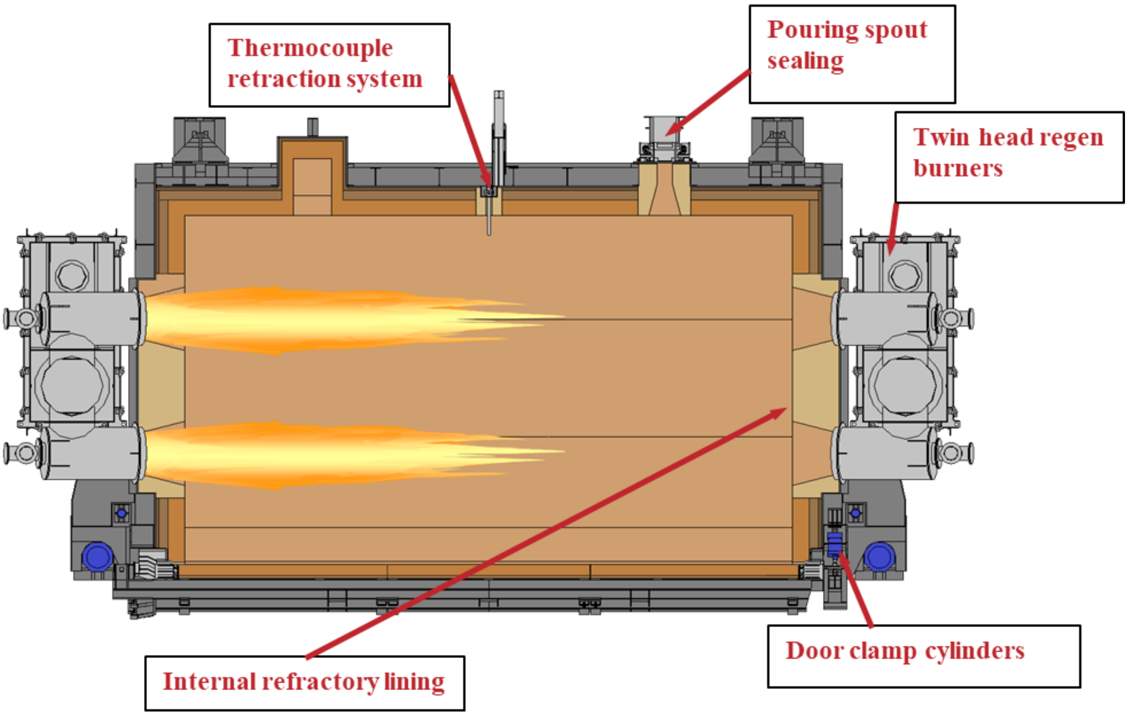

Figure 2. Plan view of a single chamber furnace, showing typical features.

Waste gases are released to atmosphere and with correct pressure control on the furnace we can ensure that cold air is not entrained into the furnace. Clamping and sealing of the main apertures on the furnace further reduce unwanted entrainment of external air. Occasionally, waste gases are released via fume treatment plant to bring emissions down to National or local regulatory levels which adds to the overall Capital Expenditure (CapEx) cost of the installation.

Different types of combustion systems can be employed to enhance the combustion efficiencies of the furnaces; traditional cold air burner systems have been the backbone of furnace heating for over a century, regenerative burner systems and recuperative systems allow us to pre-heat the combustion air using the hot waste gases from the furnace which enhances combustion efficiency. There are also oxygen enrichment and oxyfuel systems that avoid heating up non-combustible components of the combustion air (predominantly nitrogen gas) which eventually get released from the furnace, contribute nothing to the combustion process and carry away a huge amount of heat from the furnace. Generally, the higher the level of sophistication, the higher the associated CapEx cost, as shown in Table 1.

Table 1. Comparison of burner technology for a 70 t single chamber furnace with 10 t/h melting rate [2, 3].

	Cold-Air	Regenerative	Oxy-fuel
Burner Gas: Typical melting consumption	3 794 MJ/t	2 529 MJ/t	2 385 MJ/t
Burning Gas: Typical holding consumption with cold air burner on	2 096 MJ/h	2 096 MJ/h	2 096 MJ/h
Typical NOx Emissions during melting (All figures referenced to 3 % O_2)	< 150 mg/Nm^3	< 200 mg/Nm^3	< 100 mg/Nm^3
Typical CO emissions during melting (All figures referenced to 3 % O_2)	< 100 mg/Nm^3	< 100 mg/Nm^3	< 80 mg/Nm^3
Typical O_2 consumption (Nm^3/h) during melting	0	0	1 500 Nm^3/h
Cost	X	5X	3X

More sophisticated furnace solutions are available when we consider recycling processes with contaminated aluminium scrap. One of the technologies employed here is the use of multichambered furnaces which combine the use of different internal chambers to conduct decoating and melting functions (Figure 3). The aim is to thermally remove volatile organic compounds (VOC) in the form of paint, lacquer and other coatings before the scrap metal is presented to the liquid metal bath for melting. This should ensure a clean melt process and minimise metal losses. As the VOC is thermally liberated from the surface of the metal it contains a significant amount of potential energy which can be incinerated inside the furnace to supplement the use of fuel at the burners. This heat is recirculated back over the scrap metal to aid the decoating process resulting in a potentially highly efficient operation. The resulting furnace designs are complex and have sophisticated recirculation systems with huge amounts of ducting to facilitate the correct circulation of waste gasses for VOC and heat distribution, therefore the potential for huge losses of heat is always a problem that must be considered. Instrumental to the furnace operations are the loading sequences which have to be regular and reliable; scrap composition is often inconsistent, and the furnaces have to be designed to handle many different types of scrap. These variances in the load can cause problems with the furnace operating cycles as the furnace has to adapt to the varying internal conditions.

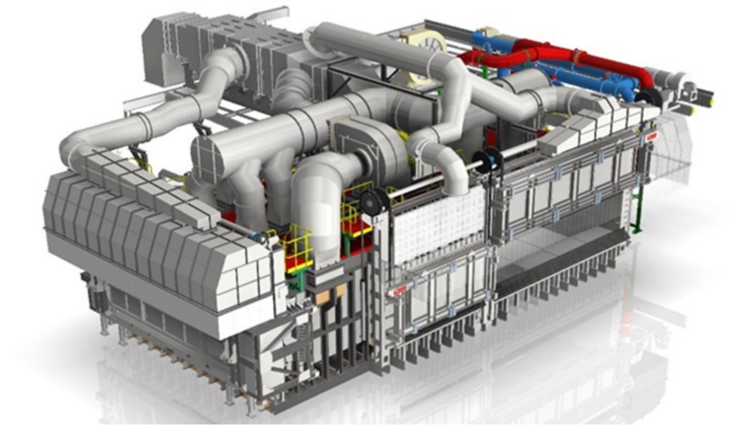

Figure 3. Typical arrangement of a multi-chamber furnace.

Furnace operating practises in the main still rely on manual intervention at the different phases of the operating cycle. This manual process relies on experienced operators with intimate knowledge of the furnaces to know when to open doors, at what time to sample the internal metal, to minimise the loading and tending times, etc. If not done correctly, these actions can disrupt the furnace operating cycles and result in unnecessary heat escape from the furnace doors. Although it must be acknowledged that some interesting developments for smart solutions, such as autonomous furnace charging vehicles, real time metal sampling solutions and internal inspection cameras and artificial intelligence-based prediction of load state exist, overall integration of these sophisticated technologies has not yet been adopted by the industry as an accepted way forward.

Semi-automated charging machine **Semi-automated tending machine**

Figure 4. Typical furnace supporting ancillary equipment.

So, what can we take from the current status of furnace technology and furnace operating practises?

- We rely on current technologies and operating practises that have been in place for some time.
- Heat loss mitigation has not really improved, we rely on correct pressure control of the furnace internal conditions and the thermal insulation properties of the refractory lining materials. This has been the philosophy for a long time.
- Heating of the furnaces largely employs fossil fuel in many cases with conventional cold air burner systems. Such systems have a low efficiency when compared to the available technologies today and losses due to waste heat are an issue. We also have the issue of emissions and products of combustion to consider.
- More sophisticated combustion system technologies are available but need a higher CapEx investment.
- More complicated furnaces for scrap recycling do not perform consistently as the scrap composition changes and the complex ducting systems can be another form of heat loss.

- We have yet to see a fully integrated smart solution for furnace operating practises.

3. Moving Forward

In this section we will discuss the developments in our industry which could have an influence on the future design basis of aluminium furnaces. Reducing energy consumption while maintaining efficiencies can be achieved with sensible operating procedures, improved mechanical layouts of furnaces, improved scrap charging mechanisms, and identifying processes with finer control tolerances to gain even small percentages of efficiency – small gains across multiple facets of a furnace design can offer tangible reductions for operating and environmental costs. Potential changes to process are identified below, with consideration on implementation challenges which may be faced.

3.1 Hydrogen

Looking firstly at clean forms of heating, hydrogen is seen as a proactive alternative to typical fuels like natural gas, offering a means of firing thermal combustion systems without the consumption of carbon. Where hydrogen supply is readily available, hydrogen combustion systems are a feasible and practical approach to offsetting hydrocarbon fuel consumption; however, there a numerous positive and negative aspects to be considered before replacing hydrocarbon fuels with hydrogen which must be carefully reviewed before a hydrogen system is proposed to a client for use on their site. When reviewing the application of a hydrogen system, these aspects must be carefully considered to ensure that the best solution for the client is offered.

Positive considerations for hydrogen include the partial or complete offset of carbon usage as well as the potential for a client to produce their own fuel on site; electrolyser technology is a feasible means of doing so. Negative considerations include higher NOx levels, and complex safety regulations.

When taken from the context of carbon dioxide production, in principle for every megawatt (MW) of burner power, 78 kilograms per hour (kg/h) of natural gas is consumed, producing more than 200 kg CO_2/h and more than 170 kg/h of water. When hydrogen is used in place of the natural gas, then 1 MW of burner power equates to 30 kg/h of hydrogen and an output of approximately 270 kg/h of water as exhaust. This is a simplification of combustion reactions and is stated purely as a means of illustrating the difference between burning either fuel with supplied atmospheric air.

Typical chemical reaction formulae for hydrogen and natural gas are shown below. These equations only consider complete combustion, and do not factor in minor species of formation such as NOx or CO. Typically, 10 % excess air is used for combustion systems to ensure that all fuel gas has been consumed.

Methane (majority component of natural gas)

$$CH_4 + 2X(O_2 + 3.76\,N_2) = CO_2 + 2\,H_2O + (2X - 2)O_2 + 2X(3.76N_2) \tag{1}$$

Hydrogen

$$H_2 + \frac{X}{2}(O_2 + 3.76N_2) = H_2O + \frac{1}{2}[(X - 1)O_2 + X(3.76N_2)] \tag{2}$$

where:
CH_4 Methane

O_2	Oxygen
N_2	Nitrogen
CO_2	Carbon Dioxide
H_2O	Water
H_2	Hydrogen
X	Stoichiometric air (X = 1) with excess air additional (X > 1 % excess air).

It can clearly be seen that combustion using hydrogen gas is more efficient in terms of gas consumption when compared to natural gas and there is a complete reduction in carbon dioxide emissions; however, the increased moisture by-product resulting from the use of hydrogen as a fuel is seen by the system in the chamber, the exhaust line and associated downstream equipment. While hydrogen uptake in the molten aluminium bath is not seen as a serious process issue, the additional moisture in the combustion atmosphere may lead to poor exhaust filtration and corrosion of downstream equipment.

Environmental concerns may not be eliminated completely, due to the propensity for hydrogen combustion to produce higher NOx levels than more common fuels, typically attributed to the hotter, faster burning flame. In addition to this, the higher flame temperatures can be a concern for refractory ceilings within the furnace chamber.

Furthermore, observation of the flame on large burners is reliably achieved with UV flame sensors and smaller combustion systems may struggle to prove flame observation due to the weaker UV emission of the flame during operation.

The use of hydrogen as a fuel for a burner brings further caveats with regards to safety. ATEX [4] and DSEAR [5] assessments need to be conducted in a finer level of detail than is normally applied to natural gas combustion systems and may preclude the use of preferred equipment due to non-compliance with the safety regulations. Consideration must also be given to the size of the hydrogen gas fuel trains; pipe bores and valve sizes are larger than that required for the same process duty as natural gas. This is an added cost for materials but also an increase on engineering time to accommodate larger valves that can be safely accessed by operators.

Overall, hydrogen is a suitable fuel which, in some circumstances, given local infrastructure, motivation for plant and projects and whether the equipment being applied is part of a new CapEx investment or an upgrade to existing system. The application of hydrogen fuel into aluminium furnaces is not at this stage a good fit for every scenario.

Further research needs to be conducted on the effect of heat transfer within the process due to the lower mass of hydrogen and air required for the combustion to meet the burner duty.

3.2 Plasma Heating [6, 7]

The use of an alternative fuel to reduce carbon emission is just one mitigation initiative, another alternative to the use of not only conventional fuels but to classic burner technology is to employ plasma torch technology. It has so far been absent from aluminium plants but is being trialled by several leading producers to establish the practicality and performance for aluminium furnace applications.

Plasma torches are not new and plasma cutting tools have been used for a long time. However, the new plasma torches use the same technology to electrify a gas stream to generate a hi-temperature plume of ionized gas but expel the plume over a wider area and up to lengths of almost 2 metres. The gas stream can use air, oxygen or an inert gas to create the plume and offers a clean way of converting electrical and gas input into heat output, typically figures of

239 kg CO_2e/MWh when clean electricity source is available and torch outputs of 5 MW seem to be achievable so far with current available designs. Electricity to heat conversion rate of 70–80 % are the proposed figures for such technologies which seems comparable to the most efficient burner systems available today.

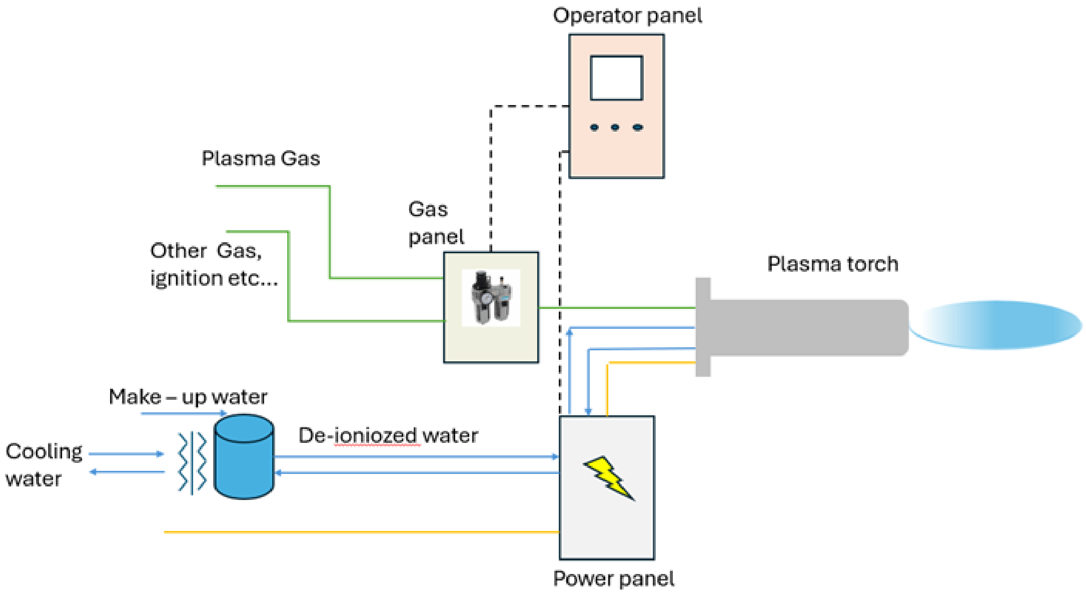

Figure 5. Typical arrangement for a plasma torch system.

The benefits of the plasma torch technology is that an efficient method of delivering heat to the furnace can be achieve with little or no green-house gas emissions. As mentioned, this technology is still relatively new to the industry and is still very much in the trial phase of its introduction. Optimization of components and suitability in a real-life application are still to be determined, but the signs are very positive. The gas medium still has to be provided at the plant and the credentials of this technology as a green technology are dependent on the source of electrical power as much as the technology itself.

3.3 Thermal Loss Mitigation

Aluminium furnaces are large structures, and the thermal losses go into hundreds of kilowatts (kW) of power during normal operation. Thermal loss mitigation is the simple process of reassessing designs to improve thermal insulation without drastically changing the structure or significantly increasing the build cost.

One of the regions of highest thermal loss is that of the molten metal bath, where losses have to be accepted in order to minimise permeation of molten aluminium into the refractory; this is referred to as the wetted areas. Regions above the wetted area are referred to as the dry area – where the combustion atmosphere is present. In the dry area, thermal losses to the environment can be reduced by improving insulation. This may initially incur additional cost but will be offset by the reduction in power consumption by the system manifesting as reduced fuel consumption.

Some large aluminium furnaces improve the thermal energy transfer to the aluminium load by using recirculation systems to stir the combustion atmosphere. These recirculation systems can cause further thermal losses to the environment as the ducts are usually fixed proud to the casing providing additional surface area for. Mitigation strategies for future designs would look to incorporate the ducting into the furnace structure, reducing both exposed surface area and the materials required.

The materials in question would include steelwork and refractory lining, as well as improving operator access to the furnace roof.

3.4 Furnace Efficiency

Melting efficiency is a key aspect for ensuring optimal furnace operation and managing fuel consumption and waste generation.

3.4.1 Combustion Chambers

Combustion chambers typically operate at 1 050–1 100 °C and rely on a combination of forced convection and radiation (primarily emitted from the working face of the refractory walls). To ensure that the melting process is as efficient as possible, the combustion chamber design must be considered to optimise circulation of the burner flows within the chamber to ensure maximum beneficial work before flows are exhausted out of the chamber. The efficiency can be improved by profiling the refractory to “steer” or “deflect” the burner flows, as well as consider the general shape of the chamber and the position of the burners.

For example, it has been observed in feasibility studies that there is a reduction in the interaction of the combustion atmosphere and the molten aluminium bath, within a furnace chamber, during full combustion on hydrogen. The reduction in mass flow within the system reduces the heat transfer coefficient between the gaseous atmosphere and liquid metal.

3.4.2 Decoating Chambers

Although chambers used to “de-coat” contaminated scrap (scrap coated with oils, paints or lacquers, etc) operate at lower temperatures (400–600 °C) and rely predominantly on forced convection to heat up the aluminium, as radiation is less influential at these lower temperatures, passive stirring of the chamber atmosphere will encourage flow interaction with the scrap, heating it up and promoting vaporisation of the contaminates.

3.4.3 Charging Logic

Aluminium melting furnaces can be expected to handle a vastly differing range of scrap types, from solid ingots to thin gauge foils compressed into briquettes and be able to melt the scrap efficiently to minimise melt losses and energy consumption. To better accommodate the range of scrap types, measurability and reactivity of the system to each scrap charge offers a route to improving overall furnace efficiency. The industry requires the development of an improved scrap charge machine, which, when a scrap charge is loaded onto the charge machine, is “assessed” to determine the general density of the charge. This density with the percentage level of contamination (by mass) would permit the furnace to adapt its firing regime to maximise removal of the contamination and maximise output, whilst minimising fuel consumption.

3.4.4 Waste Heat Recovery

There can be a significant number of waste heat sources from an aluminium melting furnace, making use of these can beneficially offset fuel consumption for the furnace. Waste heat from an exhaust flow can be used to pre-heat combustion air where a regenerative or recuperative burner is not feasible; for example, fuel consumption for a cold air burner, using 20 °C combustion air, can be reduced by circa 15 % if the combustion air is heated to 200 °C from a suitable waste heat stream. Waste heat can also be the thermal source for Organic Rankine Cycle (ORC) power generation systems that convert waste heat into a useful electrical output.

Waste heat which cannot be directly used within the furnace can be used to dry and warm scrap or for other site processes. Drying scrap can be considered as a safety practise as molten aluminium reacts adversely when it comes into contact with moisture, creating dangerous situations for operators and potential damage to furnaces. Furthermore, warm scrap reduces the total thermal work required by the furnace to meet the process requirements, offsetting fuel consumption. This may only amount to a few percent of efficiency gain; however, this may equate to a reasonable reduction in operational costs per annum of operation.

3.4.5 ORC power generation

ORC power generation from waste offers several benefits for off-setting energy consumption within an aluminium cast-house. The most direct benefit is that of electrical power generated which can offset the electrical consumption of combustion fans or other equipment associated with the operation of the furnace. Additional benefits may be seen by downstream exhaust equipment, where exhaust temperatures are lower due to the energy extracted by the ORC system (Figure 5). This reduction in thermal energy, within the exhaust, results in less dilution air being required to lower the exhaust temperature to a safe level for any associated filtration equipment, for example.

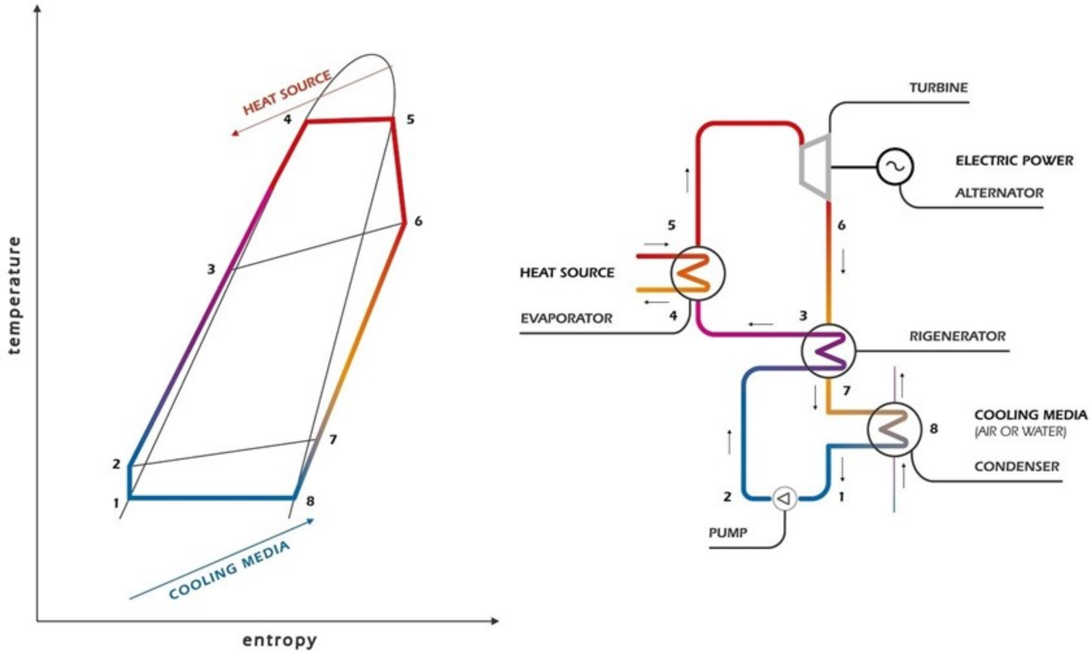

Figure 6. Organic Rankine Cycle principle [8].

Implementation difficulties on existing equipment: Integration of an ORC system into existing operational plant mainly requires the installation of heat exchangers.

3.4.6 Pre-heating Combustion Air

One format of scrap melting furnace is commonly referred to as a multi chamber furnace. These furnaces have the capability to handle clean scrap and contaminated scrap and the burner setup is usually to have regenerative burners for the main melting chamber and a cold air burner for the chamber that handles the contaminated scrap. Exhaust flow is handled by the main chamber, where the regenerative burners alternate between firing and acting as the primary exhaust route. About 80–90 % of the exhaust can be pulled through one of the regenerative burners, with the remainder discharged through an exhaust port in the wall or roof. This 10–20 % flow exits at the furnace operating temperature, nominally 1 050–1 100 °C, offering a direct thermal resource to pre-heat the cold air burner combustion air and offering significant fuel reduction.

For example, an arbitrary multi-chamber furnace has a pair of 3 MW regenerative burners and a 1.5 MW cold air burner. On full demand, a single regenerative burner will produce 4 600 kg/h of exhaust and it is assumed that 10 % will exit through the roof exhaust port; this equates to 463 kg/h. The cold air burner requires 2 100 kg/h of combustion air when on full demand, and to pre-heat this from 20 °C to 200 °C requires in the region of 108 kW of thermal energy to supply this uplift of 180 °C. Negating heat exchanger efficiency, the demand of 108 kW could be met by the 10 % exhaust flow and would cool the exhaust to 400–500 °C. The cold air burner combustion air would be pre-heated to circa 200 °C and offer a fuel reduction in excess of 15 %.

Implementation difficulties on existing equipment: The greatest challenge is integrating a new exhaust heat exchanger into an existing design. Whilst not insurmountable, careful consideration must be given to the location of the new equipment in order to minimise disturbance to the existing equipment.

3.5 Autonomous Furnace Operations

We know that the equipment technology exists now for intelligent vehicles that can take a solid load from a scrap yard and navigate, using intelligent sensor networks, to the correct position in front of a furnace for loading purposes. Intelligent hot cameras with geometrical recognition technology can determine the status of the metal bath inside the furnace by recognising the flat bath condition allowing the operators to know the ideal times to perform tending operations inside the furnace. We now have initial technologies developed to perform real time analysis of metal composition such as LIBS internal furnace lasers or spectrographic probe technology. We also have long standing technologies such automated bath thermocouple retraction systems for sampling bath temperature or EMS technologies for performing stirring and mixing functions. All of the technologies still require a centralised brain known as an operator to react and co-ordinate appropriate tasks based on the feedback from all of the equipment essentially still relying on manual intervention.

What these mentioned technologies provide us with are the initial building blocks for a completely autonomous furnace operation. With an intelligent furnace control system interlocking with this equipment there is no reason why, in the near future, a furnace cannot become operator-less, at least for normal operations, this would allow operators to be taken away from dangerous furnace operations and would allow plant teams to focus on more pressing issues that need a human such as preventative maintenance, critical operations or damage control. An autonomous furnace operation would also mean with reliable equipment monitoring furnace operational optimisation of the furnace cycle could be made. Door opening will be minimised and only undertaken as and when necessary, according to the feedback given on the internal conditions inside the furnace. If we consider that approximately 5.67 MJ/m^2·h is lost whenever a furnace door is open then the benefits of refining the furnace cycle and limiting the door opening times becomes apparent.

4. Conclusions

The initial conclusion that can be drawn is to the multitude of strategies that can be implemented to a typical “gas fired” furnace operating in the Secondary Aluminium industry. The strategies can be separated into various categories: conversion, upgrade, and passive. A furnace being adapted to run on hydrogen would be a conversion strategy, as the changes implemented require the system to operate in different parameters to that of a natural gas combustion system. An upgrade strategy could be the installation of a heat exchanger to recover heat for use with a cold air burner; general operation of the combustion system and the furnace remain effectively the same. Passive strategies are more likely implemented when a furnace is in the design stage where, for example, the refractory in the dry region of a chamber is profiled to encourage better fluid movement by the combustion products around the chamber and improve thermal energy transfer to the scrap or molten bath.

Integration of these strategies is not straightforward, tight project schedules do not often allow accommodation of development work to best optimise the process in question. Furthermore, resistance can be met when proposing the implementation of a technology which differs from the normal practices of the industry or the suggestion of changing operating procedures to make operational cost savings.

Hydrogen offers an appreciable means for furnace operators to reduce or offset their carbon fuel consumption and if a hydrogen combustion system is deemed necessary then it can be readily integrated into an existing system or new design. However, the distinct conclusion that can be drawn from hydrogen as an option is that it does not offer an avenue towards improving efficiency and reducing overall energy consumption. The combustion air fan may have a lower demand than that of natural gas, however; the thermal transfer is partially reduced as a result of the lower mass input into the furnace.

Some of the technologies discussed are still very much in the initial stages, the use of plasma torches to replace conventional burner systems show positive avenues for de-carbonisation while offering high level heating efficiencies and we wait for further feedback on the actual application of this technology in the field. Autonomous furnace operations can offer another way to optimise furnace operating efficiencies and creating a safe operation by removing operators from the danger zones, the equipment exists to enable us to create this but is still not yet widely accepted in our industry.

All other strategies and technologies presented in the paper are equally applicable to each furnace in our industry. What we can say is that the practicality of adopting them will be dependent on several factors and not all solutions will be applicable to each furnace or plant, depending on the technical and layout constraints within the plant, local infrastructures etc. However, what this paper shows is that there are many means to improve furnace efficiency, reduce consumption and ultimately reduce our impact on the environment, there is not a ‘one size fits all’ solution but as we mentioned at the start of this paper, small gains across multiple facets of a furnace design can offer tangible reductions for operating and environmental costs.

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