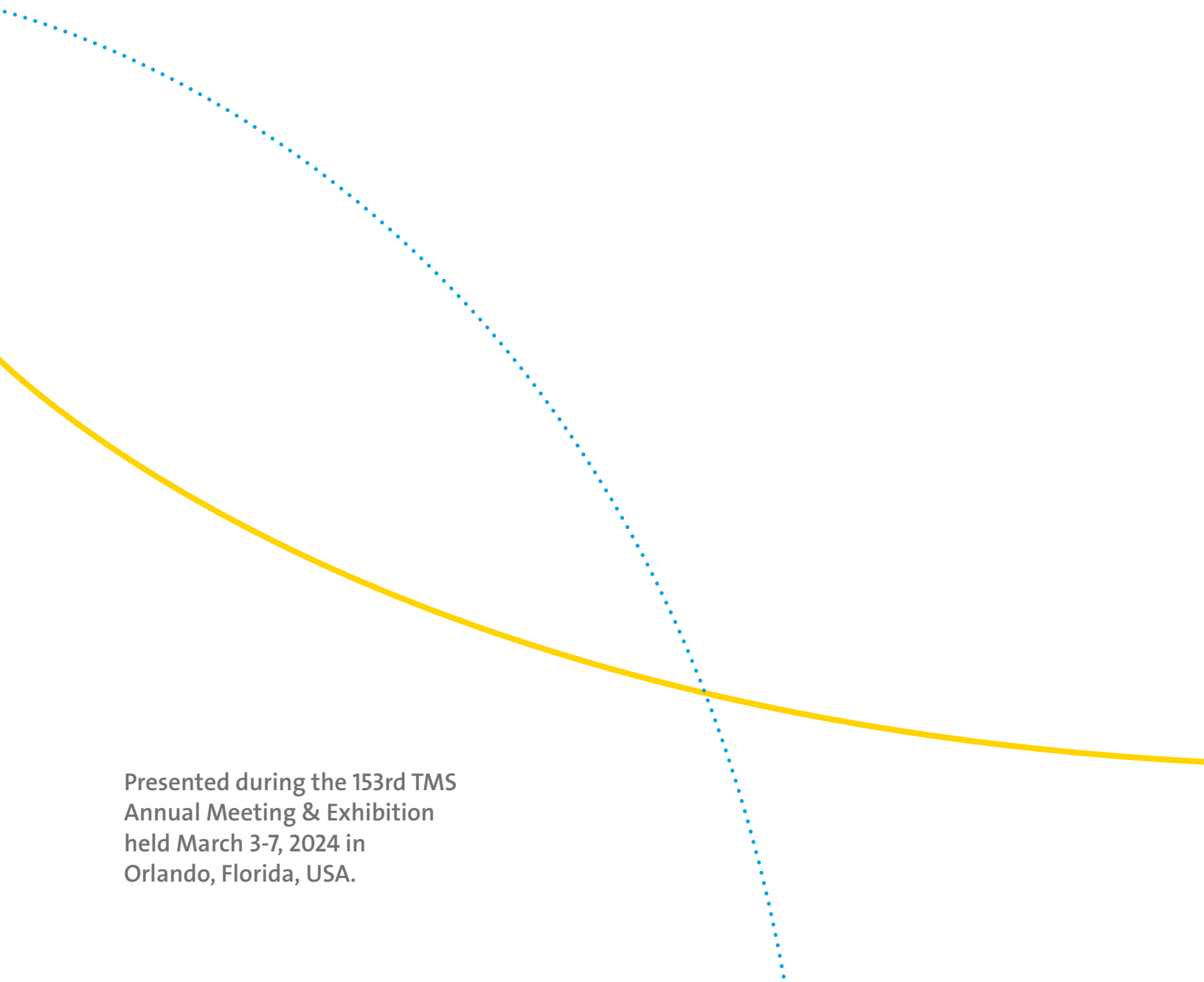


Pathways to reduce operational carbon footprint in secondary aluminum melting

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A decorative graphic consisting of two curved lines. One is a solid yellow line that starts on the left side of the page and curves downwards towards the right. The other is a dotted blue line that starts at the top left and curves downwards, crossing the yellow line and continuing towards the bottom right.

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Abstract

Economic and environmental pressures are driving change in the modern aluminum industry, compelling manufacturing sites to optimize their processes to drive down costs and reduce environmental impact. Secondary aluminum melting (recycling) requires only 5-10% of the energy needed to produce primary aluminum — reducing carbon emissions and providing cost savings for the producer and consumer but is still a major source of greenhouse gases because of the growing size of the secondary market. Significant improvements in carbon footprint and energy efficiency can be made to aluminum remelting by using smart oxy-fuel burners, low carbon intensity fuels, and Industry 4.0 tools.

In this paper, we discuss different pathways to reduce total CO₂ emissions from secondary melting furnaces. First, a novel smart burner will be discussed. This next generation oxy-fuel burner helps to reduce specific fuel consumption. The burner is a “transient heating” burner that enables automatic control of energy into various locations of the furnace, based on feedback from furnace sensors. Second, we discuss how the use of low carbon intensity fuels like hydrogen and ammonia can help reduce or eliminate CO₂ emissions. Finally, we present how the use of oxy-fuel combustion technology combined with low carbon intensity fuel can help optimize overall energy cost for secondary melting furnaces. These pathways can assist manufacturers in choosing the optimal solution to decarbonize their melting furnaces.

Introduction

Secondary aluminum melting furnaces provide an energy-efficient pathway to recycle used aluminum products and scrap. These secondary aluminum processes consume about 5-10% of the energy needed to manufacture primary aluminum, thereby providing environmental and economic benefits. The focus on decarbonization of the industrial sector to achieve net-zero carbon emissions has bolstered interest from producers in diverse ways to reduce and/or eliminate the carbon-footprint of their secondary melting furnaces. This paper focuses on how the use of next-generation oxy-fuel burners and low carbon intensity fuels can help lower the carbon footprint of secondary melting furnaces.

Pathways to reduce carbon footprint of secondary melting furnaces

A major source of carbon generation from secondary melting furnace operation is the use of carbon-containing fuels that are used for process heating. Most of the fuels used currently for process heating with combustion systems contain carbon and hydrogen which get converted into carbon dioxide (CO_2) and water vapor (H_2O) as major products of combustion, in addition to minor species like NO_x , CO , PAHs, unburnt hydrocarbons, or fuel leaving the flue etc. The CO_2 emissions from combustion are the major source of greenhouse gas (GHG) emitted from secondary melting furnace operations.

Oxy-fuel combustion is a good pathway to achieve partial decarbonization of secondary melting furnaces. The use of oxy-fuel combustion systems in reverb and rotary furnaces allows for the reduction of the fuel usage and, therefore CO_2 emissions, by as much as 40% as compared to conventional cold air-fuel combustion systems because oxy-fuel flames are more effective in transferring energy to the melt. In oxy-fuel systems, the higher heat transfer rate to the melt is due to higher flame temperatures, higher flame emissivity, and the absence of diluent nitrogen (that carries the heat with it out of the flue) [1].

Given the need to achieve net-zero carbon emissions from furnace operations, producers can switch to biofuels or alternative fuels like hydrogen (H_2) or ammonia (NH_3) that don't contain carbon. While the combustion of H_2 or NH_3 will not produce any CO_2 leaving the flue, it is critical to take into account the pathway by which these fuels

are produced and how much CO_2 emissions are associated with the production of these fuels. Carbon capture at the furnace exhaust is another potential route to reduce CO_2 emissions. However, the use of carbon capture, storage, and transport or utilization would be very challenging to implement on reverb furnaces as compared to switching the fuel type to non-carbon-based fuels or biofuels. Carbon capture is difficult in secondary melting because of the smaller scale of reverb furnaces and the need to utilize or sequester the captured CO_2 . Lastly, N_2O , and unburnt fuel like CH_4 have higher lifetime GHG potential as compared to CO_2 [2]. The use of alternative fuels like hydrogen and ammonia can increase the NO_x and N_2O emissions from combustion processes due to thermal NO_x formation and/or fuel-bound NO_x formation [3]. Therefore, it is critical for the burner to be designed to minimize the NO_x formation from use of these alternative fuels, and the GHG potential of NO_x and N_2O should be accounted for when switching the fuel type.

Partial decarbonization Use of oxy-fuel burners

Oxy-fuel burner technology can be used in current reverb and rotary furnaces to achieve either of two goals: increase the furnace production rate or decrease the fuel usage per ton of material produced. Rotary furnaces have higher efficiencies than reverb furnaces [4] due to a higher heat transfer rate driven by direct contact between the hot refractory and the melt, and the mixing action of rotation. As a result, use of oxy-fuel is a natural fit for rotary furnace as

the maximum available energy from oxy-fuel can be absorbed by the melt. The use of multiple burners in a rotary furnace [5] can provide enhanced process benefits by providing a means to reduce uneven heat distribution in the furnace and incomplete combustion products leaving the furnace flue.

In reverb furnaces, the oxy-fuel burner operation can be tuned to match the producer needs to either partially convert the furnace operation to oxy-fuel (boost application) or convert to a full oxy-fuel system. The effective use of oxy-fuel combustion has two critical aspects associated with it, design of the burner, and the correct installation location to maximize its benefits. The remainder of this discussion focuses on the use of smart oxy-fuel burners in reverb furnaces.

Oxy-fuel burners need to be designed in such a way that they can provide efficient heat transfer to the melt while minimizing any adverse impacts of using oxygen as the oxidizer and its inherently higher flame temperatures as compared to air-fuel burners. These devices can be designed as smart burners using Industry 4.0 tools to automatically regulate firing rate, equivalence ratio, and/or the amount of energy input from individual burners (in the case of multiple burners used in a furnace).

Proper location and installation of oxy-fuel burners in the furnace is equally important to extract the maximum theoretical benefits that this technology can deliver. Computational fluid dynamics modeling (CFD) is a good tool to simulate the whole furnace operation and identify the optimal location to install the burners.

Horizontal Transient Heating Burner (HTHB) technology

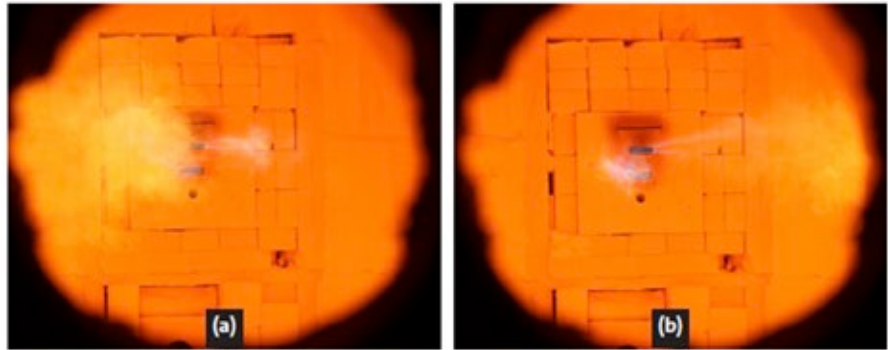
The Air Products Horizontal Transient Heating Burner (HTHB) technology [6] is a smart technology that allows directional control of flames in a furnace based on feedback from smart sensors positioned within the furnace.

Figure 1 presents photographs of flames (natural gas (NG) as fuel and oxygen (O_2) as oxidizer) showing directional change of the flame from the left to the right side of the furnace. **Figure 1 (a)** shows the left side flame (active flame) is providing about 80% of the total heat output from the burner to the left and **Figure 1(b)** shows the right-side flame is delivering the major portion of the burner thermal output to the right.

The modulation of the flame direction from left to right and vice versa can be based on a fixed frequency or on feedback from sensors installed in the furnace. This ability to regulate the flame direction helps to solve several challenges faced by typical stationary flame oxy-fuel or conventional regenerative (regen) burners. In particular, the ability to move the flame around the furnace helps to achieve more uniform energy distribution in the furnace and minimize localized heating of the melt.

Figure 2 shows CFD results of the

Figure 1: Two-nozzle HTHB technology operating in a reverb furnace (a) 100% (NG- O_2) flame image with left flame active, (b) 100% NG- O_2 flame image with right flame active

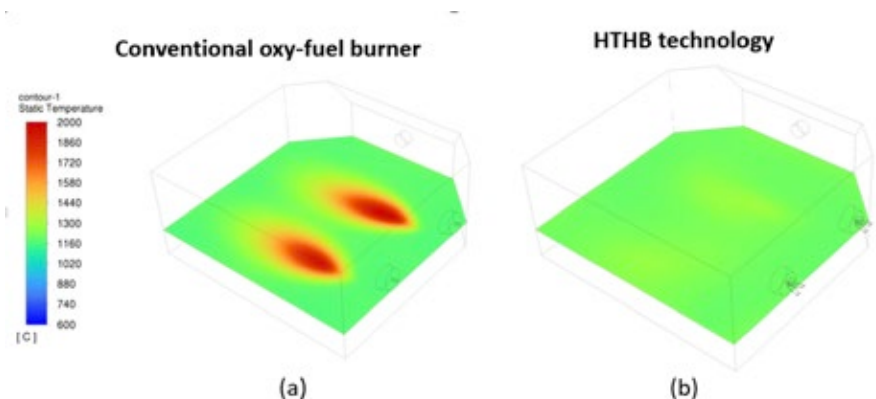


comparison of temperature profiles near the aluminum melt surface in a reverb furnace for two different burners: stationary conventional oxy-fuel burner vs. HTHB technology. In both cases, the reverb furnace has two burners installed that operate at identical firing rates and global equivalence ratios. The comparison of the two plots shows that HTHB technology is able to achieve a more uniform temperature distribution throughout the melt surface. The more uniform temperature in the furnace helps to reduce the peak temperatures on the melt surface and reduce cold spots as compared to the conventional oxy-fuel burner systems. The HTHB technology can produce

lower peak temperatures due to delayed mixing through both fuel and oxidizer staging, and these reduced peak temperatures help to decrease metal losses due to oxidation and reduce cold spots, helping to improve the energy efficiency of the furnace.

Additionally, this next-generation transient heating technology produces lower nitrogen oxides (NO_x) by up to 40% as compared to conventional oxy-fuel burners, for both conventional fuels (NG) and mixtures of conventional (NG) and alternative fuels (H_2) [6]. Lastly, staging of the oxidizer away from the melt surface can assist in reducing the oxygen near the bath surface, which can help to reduce metal oxidation and increase metal yield.

Figure 2: Comparison of temperature profile at the aluminum melt surface (a) conventional oxy-fuel burner, (b) HTHB technology



Furnace simulation using CFD

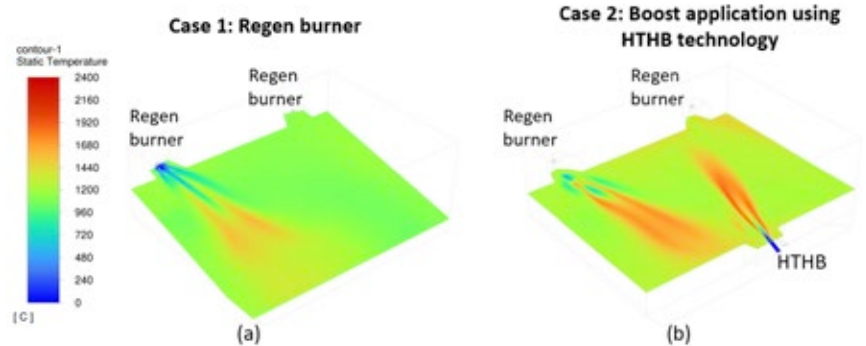
The design of new generation oxy-fuel burners is the first part of the equation to solve the challenge of implementing oxy-fuel combustion in reverb furnaces. CFD can be used to answer several critical questions such as: how and where in the furnace should the burner be installed? How will the installation of this burner impact the flow field in the furnace? In the case of a boost application, how does the operation of two burners impact the flame development from each individual burner? Additionally, in the case of larger furnace sizes, multiple burners or a combination of different burners (roof-mounted transient burners or sidewall mounted transient burners) can be used in the same furnace. CFD plays a critical role in identifying optimal locations of these burner systems.

A reverb furnace of 15-ton capacity was simulated using CFD to find the optimal location of the oxy-fuel burner for a secondary aluminum melting operation. The aim of the study was to either reduce the fuel usage or increase the production rate, as needed, based on customer-specific goals. The HTHB technology was evaluated for a boost application study with a target to replace about 50% of energy input to the furnace with an oxy-fuel burner. The existing air-fuel system is a two-burner regen system and uses natural gas as fuel.

Figure 3 (a) displays this air-fuel case and shows the temperature field in the burner plane when the left side of the burner is operating. **Figure 3 (b)** shows the boost application and the temperature field in the HTHB

flame plane. The figure shows the evolution of two flames (one from the regen burner and the second from the HTHB) in the furnace with minimal interaction. The development of the flames in two different directions is intentional to achieve more uniform heat transfer throughout the melt surface and reduce cold spots in the furnace. The CFD results demonstrate that when the total firing rate was maintained between the two cases, the melting thermal efficiency improved by 7% and the melting time was reduced by 14%.

Figure 3: Comparison of temperature profile in the burner plane (a) Regen system, (b) Boost application using HTHB technology.



HTHB installed in a reverb furnace

A HTHB burner was installed in a reverb furnace with a regen burner in a boost application at a secondary aluminum melting operation in Europe. The burner and related installation allow a transition to a system with energy input almost exclusively from the oxy-fuel combustion system. This flexibility allows the customer to meet increased production demand.

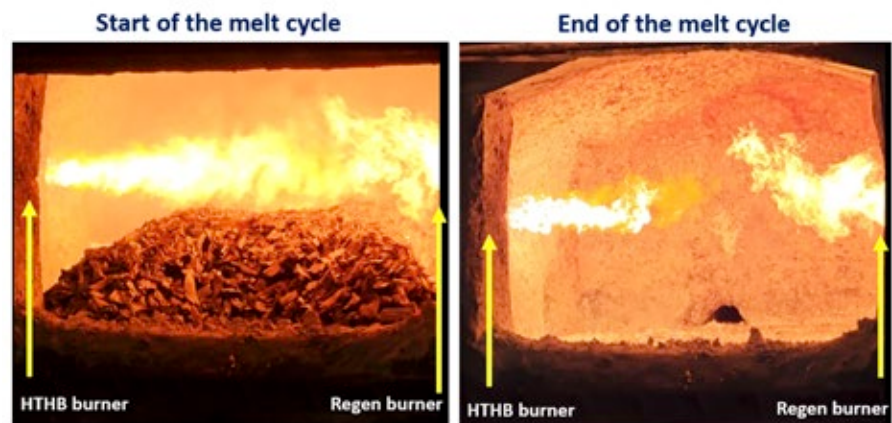
Figure 4 shows an image of the HTHB technology installed on a furnace wall. The installation at the site involved supply of oxygen, new fuel and oxygen flow control skids, as well as a burner control system.

The burner has been commissioned and operation has been smooth to date. **Figure 5** shows the flame images from HTHB technology during the start of the melt cycle and at the end of the melt cycle. The flame from the transient heating burner is long, covering about 2/3 of the reverb furnace width, and is sootier due to fuel rich combustion from the individual flames. This allows the energy from the flames to penetrate much deeper along the furnace width and increase the radiative heat transfer from the soot particles to the melt. The authors are waiting to collect more data in the coming months and the results will be shared once this data has been analyzed.

Figure 4: HTHB mounted on a reverb furnace wall.



Figure 5: Flame images from reverb furnace: (a) Start of the melt cycle (b) End of the melt cycle



A roof-mounted version of the Air Products Transient Heating oxy-fuel burner system has been installed in several reverb furnaces [4,7]. The operations have achieved productivity increases of up to 35%, up to 20% lower metal losses, and decreases in fuel consumption of up to 45% [4,7]. The increase in thermal efficiency helps to reduce the specific fuel consumption (SFC) and lower the carbon footprint of the furnace operation. These examples of using

oxy-fuel combustion illustrate that the secondary aluminum industry can benefit from the use of next-generation smart oxy-fuel burners to reduce their carbon footprint from combustion processes, while improving furnace performance (furnace thermal efficiency, improved productivity, improved furnace yield) to obtain economic benefits.

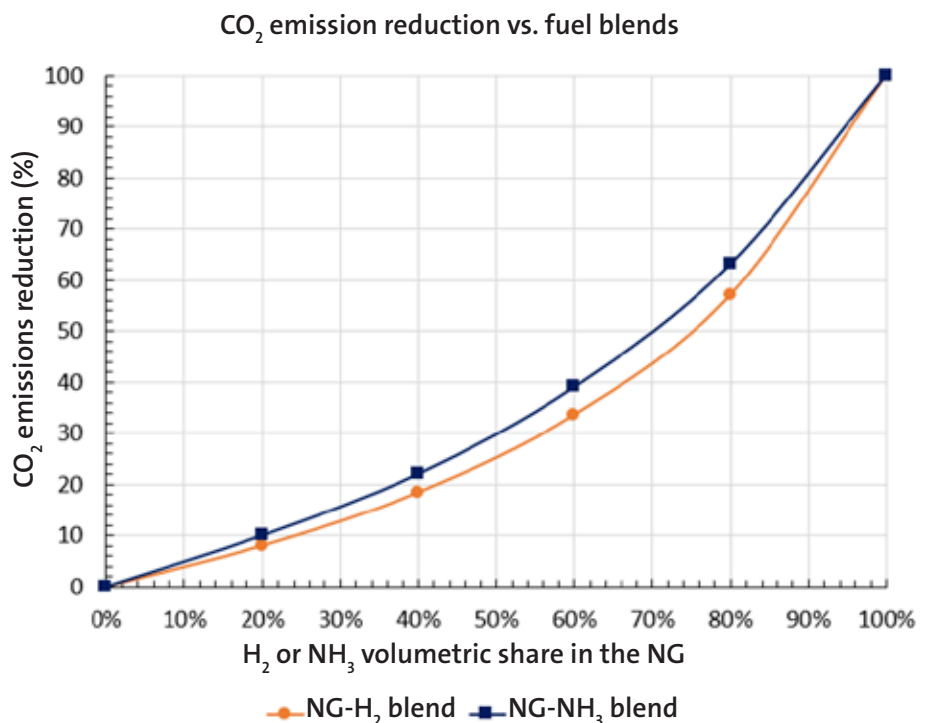
Impact of the use of low-carbon intensity fuels on decarbonization of melting furnaces

The use of oxy-fuel combustion can help accomplish partial decarbonization of secondary melting furnaces. However, to reduce the carbon footprint further, use of alternative fuels like low-carbon intensity hydrogen or ammonia are attractive options. Fuel consumption directly relates to CO₂ emissions, e.g., for every million Btu (MMBtu) of natural gas burned, 116 lbs. of CO₂ are released into the atmosphere [8]. These exhaust flue CO₂ emissions are eliminated when we change the fuel to H₂ or NH₃. The major products of combustion of H₂ and NH₃ are water-vapor (H₂O), and water vapor (H₂O) and nitrogen (N₂), respectively. No CO₂ is emitted, thereby achieving zero exhaust flue CO₂ emissions.

Figure 6 shows theoretical CO₂ emissions reduction potential from flue exhaust for different fuel blends of natural gas-hydrogen and natural gas-ammonia. The base fuel used in these calculations is natural gas. The figure doesn't consider CO₂ associated with the production of H₂ and NH₃ and any NG leaks in the supply chain. Hydrogen and ammonia fuels have carbon intensity associated with their production and this carbon intensity depends on the production route used. It is important to check with the fuel supplier regarding the carbon intensity associated with the fuel production and calculate 'actual' CO₂ reduction possible when switching the fuel type to NG-H₂ or NG-NH₃ blends. For hydrogen and ammonia to be considered low carbon, they must be produced by emitting less than a certain limit of CO₂ emission/MJ of fuel; for example, in Europe for hydrogen this limit is fewer than 20g CO₂e/MJ of hydrogen (46.5 lbs CO₂e/MMBtu) [9]. Additionally, Figure 6

displays that for a given volumetric blend of H₂ or NH₃ with NG, NG-NH₃ fuel blend has a slightly higher CO₂ emission reduction potential as compared to the NG-H₂ fuel blend due to the higher heating value (HHV) value of ammonia (435 Btu/scf) is greater than hydrogen (343 Btu/scf). As a result, at a fixed volumetric fuel blend ratio, the NG volumetric flow rate is reduced more in NG-NH₃ mixture as compared to the NG-H₂ mixture.

Figure 6: CO₂ emission reduction for NG-H₂ and NG-NH₃ blends.



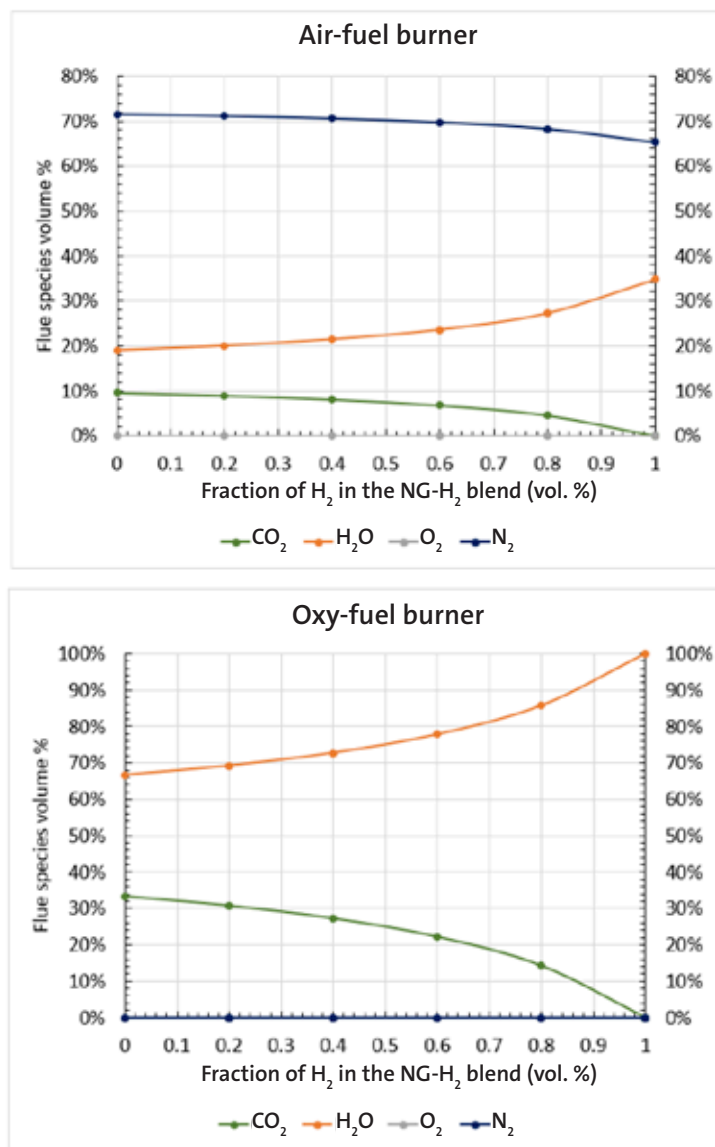
Considerations for the use of hydrogen

Air-fuel, oxy-fuel, or air-oxy-fuel burner systems

Another important consideration is whether to use an oxy-hydrogen burner, air-oxy-hydrogen or an air-hydrogen burner. Oxy-fuel flames are more effective in transferring energy to the melt as compared to those from air-fuel burners. The absolute improvement in thermal efficiency and therefore, fuel usage per lb. of material processed, depends on several factors, including (but not limited to) type of furnace, air leakage in the furnace, whether it has undergone a full or partial conversion to oxy-fuel combustion. The previous field results show that the fuel usage with oxy-fuel burners can be reduced by as much as 45% [4,7]. This is important as hydrogen, in particular low carbon intensity hydrogen that has low carbon associated with its production, is more expensive as compared to conventional fuels. Therefore, with the use of oxy-fuel combustion systems, the total fuel cost can be reduced as compared to air-fuel systems.

Another consideration is that the furnace atmosphere composition when using air-fuel burners versus oxy-fuel burners is significantly different. **Figure 7** compares the major species produced from combustion of NG-H₂ fuel blends for both air-fuel and oxy-fuel burners. At any particular fuel composition, the use of oxy-fuel burners increases the volume fraction of CO₂ and H₂O in the furnace atmosphere. Additionally, as the fraction of hydrogen in the fuel increases, the concentration of water vapor increases inside the furnace. This increase in the concentration of water vapor, associated with an increase in the use of hydrogen and/or change to an oxy-fuel system,

Figure 7: Comparison of change in major products of combustion for different NG-H₂ fuel blends (a) air-fuel burner (b) oxy-fuel burner



in the furnace may impact the product quality and increase the metal oxidation rate. This should be considered when evaluating various fuels and combustion systems.

Furthermore, NO_x emission is another parameter that could be different for oxy-fuel and air-fuel burners. The use of oxy-fuel burners can help reduce the total NO_x emissions as compared to an air-fuel burner primarily, because of the absence of nitrogen in the oxidizer stream. Practically, due to the pressure balance in the furnace, oxy-fuel burners may produce NO_x

as a function of air leakage in the furnace.

Lastly, use of an air-oxy-fuel burner can be an interesting option to consider as well. Air-oxy-fuel burners can provide operational flexibility, allowing the combustion system to accommodate the varying needs of different furnace cycles and the ability to switch operation from oxy-fuel mode (melting mode) to air-oxy-fuel mode (holding mode).

Conclusions

Decarbonization of secondary melting furnaces can be achieved by use of oxy-fuel combustion systems and low-carbon intensity fuels, like hydrogen and ammonia. The use of smart oxy-fuel transient heating technology provides a practical way to achieve partial decarbonization of furnace operations. Alternative fuels like hydrogen and ammonia further provide a route to eliminate exhaust flue CO₂ emissions, thereby achieving full decarbonization of combustion processes. The 'actual' CO₂ reduction potential using these fuels will depend on the hydrogen and ammonia production route, which would in turn depend on the local geographic conditions (availability of renewable energy or average carbon associated with electricity available in the region, carbon intensity of hydrogen production, etc).

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