Decarbonization of Secondary Aluminum Melting

Oxy-Fuel Combustion and Low-Carbon Intensity Fuels

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Introduction

Reverb or secondary melting furnaces are an effective way to achieve a global circular economy for aluminum supply. The recycling of aluminum uses up to 95% less energy compared to the primary production route, and global production of secondary aluminum has increased by 86% from 2000 to 2015.[1] In 2015, the total amount of secondary aluminum produced accounted for about 22% of the total global aluminum production.[1] This increasing trend in secondary aluminum production will continue to grow in the future as more aluminum becomes available through old scrap metal and aluminum manufacturers are pushed to reduce their carbon footprint to move towards net-zero goals. The increase in the secondary aluminum market size, along with the global effort towards decarbonization, creates pressure on producers to find innovative ways to decarbonize their operations.

The need for decarbonization of high temperature melting furnaces has bolstered interest in the use of oxy-fuel combustion systems and low-carbon intensity fuels. Both options provide a pathway to decrease the carbon footprint of new and existing furnaces, as they are suitable for retrofit. The use of oxy-fuel combustion helps to increase the overall thermal efficiency and production rate of a furnace.[2] This increase in efficiency helps to reduce the specific fuel consumption and, hence, helps to lower the carbon footprint of the furnace operation.

Additionally, use of low- or zero-carbon intensity fuels like hydrogen is another route to reduce carbon dioxide (CO_2) emissions from furnace operations. It is important that the hydrogen is produced from a source that has a low-carbon intensity. The next generation of burners needs to be flexible so that they can operate using traditional fuels (e.g., natural gas) and mixtures of traditional and low-carbon intensity fuels (e.g., hydrogen, ammonia, etc.).

This paper focuses on the performance of the patent pending Horizontal Transient Heating Burner (HTHB) technology developed by Air Products. It discusses using oxy-fuel burner performance using conventional fossil fuels and mixtures of conventional and low-carbon intensity fuels in an industrial scale combustion furnace. Additionally, this paper presents results from computational fluid dynamics (CFD) simulations, demonstrating how the use of oxy-fuel combustion and the use of hydrogen as a fuel impacts the melting performance of a furnace. Theoretical and experimental data on CO_2 savings and the impact of furnace atmosphere composition on refractory, performance, and aluminum quality using oxy-fuel systems (commercial installation results) and low-carbon intensity fuels (with CFD results) are also presented to enable manufacturers to choose the optimal solution to move towards decarbonization for secondary melting furnaces.

Laboratory Test Results

The new generation HTHB technology is a double-staged transient heating burner that enables automatic control of energy into different locations of the furnace, based on feedback from strategically positioned sensors.[3-4] The burner is designed to direct heat to cold areas

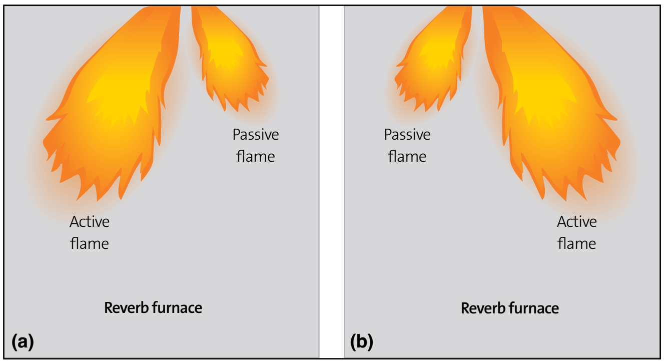

Figure 1. Illustration of dual-nozzle HTHB technology operating in a reverb furnace (top view).

of the furnace to increase thermal efficiency. For example, when the left-side flame is operating in active mode (delivering 70-90% of total burner heating capacity), energy is transferred to left side of the furnace (Figure 1a). When the right-side flame is operating in active mode, energy is transferred to the right side of the furnace (Figure 1b).

The HTHB technology is also configured for both fuel and oxidizer staging. The double staging achieves low nitrogen oxide (NOx) generation, which can be up to 40% lower than conventional oxy-fuel burners. The oxidizer staging of the burner also helps to reduce the oxygen near the bath surface, which can help avoid metal oxidation. In addition, the burner is fuel-flexible and can operate with traditional fuels (e.g., natural gas) and low carbon intensity fuels (e.g., hydrogen) and/or mixtures of different fuels.

The burner technology can be used in current air-fuel reverb furnaces as a retrofit burner. This burner can be used in conjunction with other air-fuel or oxy-fuel burners or as an independent oxy-fuel burner in melting furnaces for improved furnace operation that can provide faster melt times, increased energy efficiency, fuel savings, and production increases. Additionally, the burner can be roof- or wall-mounted, where the two configurations can be used together in the same furnace to improve performance.

The HTHB oxy-fuel technology was tested in an industrial scale laboratory furnace at a firing rate of 5 million Btu/hr. The burner was tested in oxy-fuel mode using natural gas, hydrogen, and natural gas/hydrogen blends. Figure 2 presents photographs of flames during burner operation for different fuel types and operating modes. Figures 2a-b illustrate burner operation using natural gas with two fuel nozzles, with the left and right fuel nozzles active, respectively. The fuel-rich active flame promotes soot formation, thereby increasing the flame radiation and producing a local reducing atmosphere above the bath surface. By providing the flexibility for the burner to operate under dual operating modes (with one fuel nozzle being active while the other is passive or with both of the nozzles equally active), the secondary aluminum plant is able to adjust to their operating needs and adjust for changes in the fuel composition.

With the ability to operate with different fuels (natural gas, hydrogen, or mixtures of natural gas and hydrogen), the burner can be tuned to meet individual furnace requirements. Figures 2c-d show burner operation using a natural gas/hydrogen blend at two different compositions: 60% NG/40% H_2 by heating value and 10% NG/90% H_2

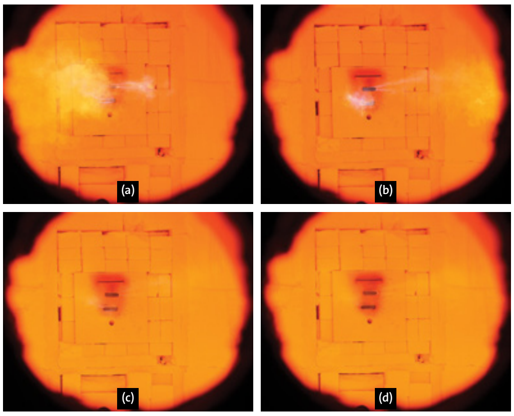

Figure 2. HTHB flame variations within a furnace, showing (a) a 100% NG-O_2 flame with left flame active, (b) a 100% NG-O_2 flame with right flame active, (c) a 60% NG/40% H_2 fuel by heating value-O_2 flame with both flames active, and (d) a 10% NG/90% H_2 fuel by heating value-O_2 flame with both flames active.

by heating value. When comparing Figures 2a-b to Figures 2c-d, the visible radiation of the flame can be seen to significantly decrease as natural gas is replaced with hydrogen, which can be attributed to the lower carbon content of the fuel.

Impact on NOx Emissions: In reverb furnaces, air leaks into the furnace during normal operation. This is because the furnace operates at slightly negative or neutral pressure compared to the external atmospheric pressure and is not airtight. This air influx results in nitrogen entering the furnace atmosphere. Additionally, in furnaces that use both air-fuel and oxy-fuel burners (e.g., in boost applications), nitrogen is introduced in the furnace from the air-fuel burner. This nitrogen interacts with the oxy-fuel flame, which forms thermal NOx.

The dual stage nature of the HTHB technology lowers the peak flame temperatures by operating away from the stoichiometric point, which reduces the NOx formation tendency of the burner. Figure 3 shows a comparison of the normalized NOx emissions (lbs/million Btu) between a conventional oxy-fuel burner and the HTHB technology, as a function of percent air leakage into the furnace. The HTHB results are presented for two cases with two different types of fuels: one with natural gas and another using a 70% natural gas/30% hydrogen mixture (by heating value).

The HTHB technology is shown to generate lower total NOx emissions by as much as 40% compared to the conventional oxy-fuel burner. The total NOx emissions from the HTHB technology are similar when operated with natural gas or a mixture of natural gas-hydrogen fuel mixtures (taking into account measurement uncertainty and

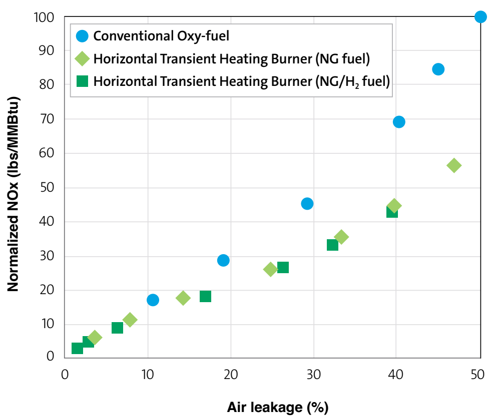

Figure 3. Impact of furnace air leakage on normalized NOx emissions for a conventional oxy-fuel burner, HTHB technology for natural gas, and 70% NG/30% H_2 hybrid fuel.

furnace operating factors). In addition, the CO_2 emissions were below 15 ppm for all operating modes.

Results from Retrofitting Existing Reverb Furnaces

Existing reverb furnaces can be retrofitted with oxy-fuel burners to replace a portion of energy coming from air-fuel burners. This mode of furnace operation can be called a boost/hybrid furnace operation where a furnace has both air-fuel and oxy-fuel burners. The use of oxy-fuel burners can help in two important ways: to increase the production rate of the furnace and to decrease the specific fuel consumption. For hybrid/boost applications, the location of air-fuel and oxy-fuel burners in the furnace is critical to provide optimal benefits. CFD simulations are generally used to identify the ideal locations of these burners to optimize the heat input to the melt and minimize the oxygen concentration near the bath surface, thereby improving metal yield.

CFD simulations were carried out to investigate the performance of a 62,000 lb capacity, natural gas-fired, aluminum remelting furnace for the purpose of increasing the production rate and reducing carbon dioxide (CO_2) emissions. These simulations helped to understand how the replacement of an air-fuel burner with an oxy-fuel burner changes the thermal performance, exhaust gases, and key aspects near the bath surface (oxygen, water vapor). Additionally, it showed how changing the fuel from natural gas to natural gas/hydrogen mixtures and to hydrogen impacts these key parameters.

The simulations included four scenarios, which compared the standard air-fuel design with hybrid cases; firing natural gas, 30% hydrogen blended with natural gas, and 100% hydrogen. The CFD simulation results are shown in Table I.

The furnace design for the base case scenario (using a standard air-fuel burner) had two sets of 10 million Btu/hr regenerative-type burners, firing a total of 20 million Btu/hr into the furnace. The melting time was 4.1 hours, with a specific fuel consumption of 1,328 Btu/lb of material charged into the furnace.

The remaining three hybrid/boost cases replaced one set of regenerative burners with the dual-staged HTHB oxy-fuel technology. The HTHB was sized to fire at 11.6 million Btu/hr to target a production increase of 25%, with a total firing rate of 21.6 million Btu/hr. The simulation showed that oxy-fuel combustion provided a significant improvement in melt rate.

In the first hybrid case, the HTHB utilized natural gas as the fuel. The use of the burner was found to reduce the melting time from 4.1 to 3.0 hours (compared to the base case), which provided a production increase of about 25%. Further, the oxy-fuel burner also provided a significant reduction in specific fuel consumption from 1,328

Description	Unit	Base case (air-fuel)	Hybrid/Boost Cases (oxy-fuel)		
			NG	70%NG+ 30%H_2	100% H_2
Total energy input	MMBtu/hr	21.00	21.6	22.00	22.12
Thermal Performance					
• Melting time	hr	4.1	3.0	3.0	2.8
• Fuel usage (SFC)	Btu/lb	1328	1053	1034	969
	% reduced compared to base case		20.7	22.2	27.1
• CO_2 savings* (use of green H_2— ideal scenario)	compared to base case %		20.7%	45.0%	100%

*Real scenario CO_2 savings would depend on the hydrogen production route

Table I. Comparison of thermal performance and exhaust flue composition for an air-fuel burner versus the HTHB oxy-fuel technology, considering different fuel type cases.

to 1,053 Btu/lb, a 20.7% savings versus the standard air-fuel case. The fuel consumption was directly related to CO_2 emissions, whereby for every million Btu of natural gas burned, 116 lbs of CO_2 are released into the atmosphere.[5] The specific fuel consumption savings of 20.7% correspond to a reduction in CO_2 emissions from 0.193 to 0.153 lbs CO_2e/lb of aluminum charged. This shows that oxy-fuel combustion can be used to increase productivity, save fuel and reduce CO_2 emissions.

In the second hybrid case, the oxy-fuel HTHB utilized natural gas blended with 30% hydrogen by calorific value as the fuel (70% NG/30% H_2). The remaining set of air-fuel regenerative burners also used natural gas blended with 30% hydrogen by calorific value as the fuel. The hybrid system was able to maintain its productivity performance using the natural gas-hydrogen blend with a melting time of 3.0 hours (Table I). The specific fuel consumption slightly improved over the first hybrid case, reducing it to 1,034 Btu/lb, with a total of 22.2% savings compared to the base case. This can be attributed to the improved efficiency of the combustion of hydrogen as a fuel compared to natural gas. The addition of low-carbon hydrogen as a fuel significantly improved CO_2 emissions savings, which can be reduced by as much as 45% versus the base case. This would be for an ideal case, where the carbon intensity of hydrogen production would be zero (0 lbs CO_2/million Btu of hydrogen) and the resulting CO_2 emissions would reduce from 0.193 to 0.105 lbs CO_2e/lb of aluminum charged. However, for a real-life scenario, even the production of low-carbon hydrogen will result in CO_2 emissions.

In the final hybrid case, the HTHB utilized 100% hydrogen as the fuel. The remaining set of air-fuel regenerative burners in this case also used 100% hydrogen as the fuel. The 100% hydrogen hybrid system was able to further reduce the melting time to 2.8 hours (Table I), corresponding to an increase in the production rate of 30%. The specific fuel consumption improved considerably more than the previous two hybrid cases, reducing to 969 Btu/lb, with a total of 27.1% savings from the base case, showing that hydrogen combustion can improve efficiency versus natural gas. In an ideal case, using 100% low-carbon hydrogen can eliminate CO_2 emissions. However, as with the second hybrid case, the reduction in CO_2 emissions is dependent on the conditions for producing low-carbon hydrogen.

For hydrogen to be considered low carbon, it must be produced by emitting less than a certain limit of CO_2e/MJ of hydrogen. In Europe, this limit can be as low as 20 g CO_2e/MJ of hydrogen (46.5 lbs CO_2e/million Btu).[6] There are several ways that the end user can receive hydrogen, including on-site generation, bulk deliveries, and pipeline. Bulk deliveries are typically unsuitable for delivering the quantities of hydrogen required for combustion in industrial furnaces, as significant quantities of either liquid or very high-pressure gaseous hydrogen would be needed. There is also the possibility of storing low-carbon or green ammonia on-site and cracking it into hydrogen prior to combustion, which would require liquid ammonia to be stored on-site and ammonia-cracking equipment to be installed. If the foundry is in the vicinity of a large hydrogen production facility, then it is possible to connect a pipeline directly to the site. Assuming these two options emit 20 g CO_2e/MJ of hydrogen, both would result in a reduction in CO_2 emissions of at least 37.9%, when comparing the base case to the 30% hydrogen hybrid case, from 0.193 to 0.12 lbs CO_2e/lb of aluminum charged. It is recommended that data regarding the actual CO_2 emitted during hydrogen production is collected from the hydrogen supplier to calculate actual reduction in CO_2 emissions.

When considering the options for on-site generation of hydrogen, electrolysis is the leading choice for low carbon hydrogen. If the foundry can take advantage of local wind or solar power, then it is likely that an on-site electrolyzer could make use of 80-90% renewable energy to produce hydrogen, depending on local weather conditions. The remaining power can be drawn from the grid. In the case of an electrolyzer, the carbon intensity of the regional grid should be used to calculate the savings in CO_2 emissions.

Additional Furnace Results: The simulation results also illustrated how the implementation of the HTHB and the various fuel types could impact the refractory wall temperature, oxygen mole percentage near the bath surface, and water vapor mole percentage near the bath surface using CFD simulations. The contours of wall temperature (Figures 4a-d) illustrate that the wall temperature increases in the boost cases as compared to the air-fuel case, primarily due to higher peak flame temperature of oxy-fuel flame compared to the air-fuel flame.

Oxygen concentration near the bath surface is an important parameter to control, as stray oxygen can result in bath oxidation, thereby decreasing the metal yield. Comparison of the oxygen mole percentage (O_2 mol%) contour near the bath surface in Figures 4e-h shows that the oxygen concentration stays relatively the same (~4-5% by mol%) between the air-fuel and the oxy-fuel boost cases. The transient nature, along with the dual-staged burner operation, helps to maintain the oxygen concentration to the base air-fuel case and hence, would not impact the bath oxidation adversely due to the use of oxy-fuel burners.

The water vapor concentration in the furnace is expected to change as an operation moves from air-fuel to oxy-fuel combustion, due to a decrease in nitrogen. This would further increase as the operation moves towards hydrogen-oxygen combustion due to the increase in water vapor (H_2O) production from hydrogen combustion. Figures 4i-j illustrate that in the transition from air-fuel to oxy-fuel combustion using natural gas, the maximum water vapor concentration increases from about 20% to 30-35%. The transition of fuel from natural gas to hydrogen (Figures 4j-l) demonstrates that the maximum local water vapor concentration can increase to as much as 60%. It is possible that high water vapor concentration in the furnace atmosphere can be detrimental to product quality and yield and may influence the choice of furnace

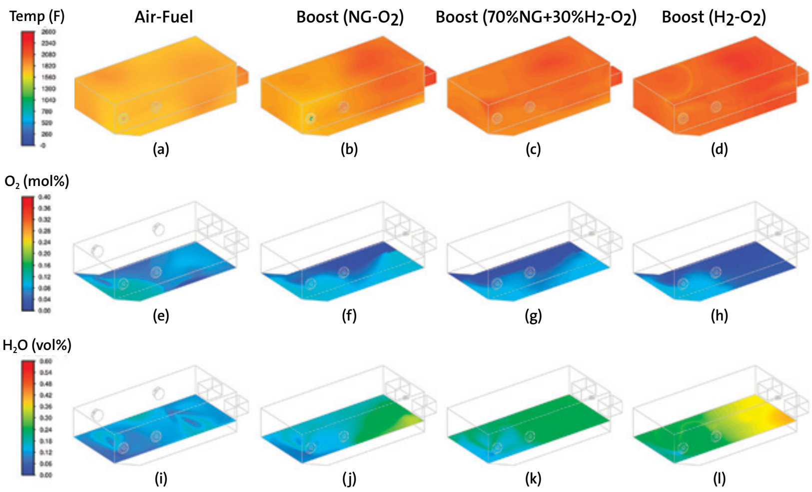

Figure 4. The effect of fuel type on furnace wall temperature (a-d), oxygen mole percentage near the bath surface (e-h), and water vapor mole percentage near the bath surface (i-l).

refractory material. This is an ongoing area of research when considering hydrogen as a fuel, and some operational and design constraints may be implemented to mitigate any risks once the problem is better understood.

A roof-mounted version of the HTHB was installed in boost applications in multiple reverb furnaces globally.[4,7] These installations were carried out using natural gas as the fuel, comparable to the boost case ($NG-O_2$) shown in Figure 4. The results from these installations indicated that the change in water vapor concentration didn't impact the melt quality, and the customers achieved productivity increases of up to 35%, up to 20% lower metal losses, and fuel consumption decreased by 45%.[4,7] These real-world examples of using oxy-natural gas combustion illustrate that the secondary aluminum industry is ready to continue the further implementation of next generation oxy-fuel burners to improve performance and reduce CO_2 emissions.

Conclusion

The use of oxy-fuel combustion systems and low-carbon intensity fuels, like hydrogen, provide a practical path to decarbonize and reduce the carbon footprint of secondary aluminum production. The lab-scale results demonstrate that the HTHB burner can operate with natural gas, hydrogen, and natural gas/hydrogen blends, while offering lower NOx performance (as much as 40%) when compared to conventional oxy-fuel burners. The flexibility of the burner technology can provide additional means to reduce the CO_2 footprint by the use of low-carbon hydrogen. The actual CO_2 reduction potential will depend on the hydrogen production route, which would in turn depend on the local geographic conditions (electricity mix, hydrogen availability, etc.).

The CFD results demonstrate that oxy-fuel technology provides significant efficiency improvements when shifting to hybrid operation compared to air-fuel burner systems. Additionally, the transition to oxy-fuel combustion maintains the oxygen concentration near the bath surface for all fuel types, indicating that the use of oxygen and hydrogen may not reduce aluminum yield. Future field testing of the technology will include using hydrogen fuel blends to better understand the impact of higher moisture concentration on the metal quality and furnace refractory, if any.

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