

FUTURE OF OXY-FUEL GLASS MELTING: OXYGEN PRODUCTION, ENERGY EFFICIENCY, EMISSIONS AND CO₂ NEUTRAL GLASS MELTING

Hisashi Kobayashi
Praxair, Inc.
Danbury, CT 06810

ABSTRACT

Over 300 commercial glass melting furnaces have been successfully converted to oxy-fuel firing worldwide since 1991 when the first full oxy-fuel conversion of a large container glass furnace took place. The main benefits of oxy-fuel conversion are fuel reduction, glass quality improvement, emissions reduction (CO₂, CO, NO_x, SO₂, particulates), and productivity improvements. Significant changes in the melting and fining behaviors were observed under oxy-fuel firing. Most furnaces required some batch modifications to optimize the glass fining chemistry and to control foam. Improved oxy-fuel burner and furnace designs have reduced alkali volatilization and silica crown corrosion. Silica crown is expected to last for a full furnace campaign, especially with new no-lime silica bricks. Today most of high-quality specialty glass products such as LCD display glass and fiber glass are melted in oxy-fuel fired glass furnaces. Oxy-fuel conversion of large soda lime glass furnaces, however, has been limited to about sixty container and ten float/flat glass furnaces due to the additional cost of using oxygen. Key factors to improve the economics of oxy-fuel fired such as efficiency of air separation technology and waste heat recovery are reviewed. The potential of using hydrogen and renewable fuels with oxygen to reduce CO₂ emissions is also discussed.
(key words: oxy-fuel, glass melting, CO₂ reduction, hydrogen combustion)

INTRODUCTION

In 1988, the U.S. Department of Energy awarded a program to Praxair, Inc. (a member of the Linde group now) to demonstrate the use of oxy-fuel combustion in a large commercial glass furnace using an on-site vacuum-pressure swing adsorption (VPSA) technology. A container glass furnace at Gallo Glass Company was rebuilt in 1991 as the first large scale oxy-fuel fired furnace¹. The successful conversion of the furnace and the demonstration of significant fuel savings (15%) and emissions reduction (80% reduction in NO_x and CO, and 30% particulates) stimulated the glass industry to adopt the new technology at a rapid rate. By 1996 about 90 commercial glass furnaces were converted to oxy-fuel firing worldwide². Although the rate of oxy-fuel firing conversions slowed down since then, over 300 commercial glass furnaces are fired with oxygen today. Most of specialty glass furnaces such as LCD glass furnaces are fired with oxygen as high glass melting temperature, relatively small furnace size and the high glass quality requirement made oxy-fuel firing more economic. Over one hundred insulation and reinforcing glass fiber furnaces have been converted to oxygen firing as large fuel savings are achieved when air fired recuperative furnaces are converted to oxy-fuel firing. About fifty container glass furnaces and about ten float/flat glass furnaces have been converted for NO_x reduction, production rate increase, and capital cost reduction.

Most of fuel efficiency gains of oxy-fuel fired furnaces come from the elimination of nitrogen contained in combustion air (i.e., about 78% N₂ and 1% Ar by volume) and the corresponding reduction in the flue gas sensible heat loss³. Fuel savings of 5 to 50% have been achieved without using any flue gas heat recovery systems under oxy-fuel firing as compared with

various air fired furnaces. Fuel savings achievable by oxy-fuel conversion depend on the type of heat recovery systems used in the air fired furnaces and their conditions. About 10 to 15% fuel savings have been achieved on the furnace campaign average for large container and float glass furnaces equipped with efficient regenerators to preheat combustion air to about 1300C. The efficiency of regenerators deteriorates with furnace age due mainly to deposits build up in the regenerator passage and to increase in air infiltration⁴. For example, specific fuel consumption for an air fired regenerative furnace may increase by 16% over 12 years (i.e., 1.35% per year)⁵, while that for oxy-fuel fired furnace without heat recovery may increase only by 6% over 12 years. Thus, fuel savings by oxy-fuel firing is relatively small in early furnace campaign and increases as the furnace ages. For fiber glass furnaces with metallic recuperators fuel savings by oxy-fuel conversion are typically in a range of 30 to 50%. Metallic recuperators can preheat combustion air only up to about 800C and the furnace energy efficiency is significantly lower than the furnaces equipped with regenerators. For small specialty glass furnaces operating at high temperatures, fuel savings over 50% have been achieved in some furnaces since small recuperators and regenerators are not very efficient.

Reduction of NO_x emissions was an important benefit and an economic driver for oxy-fuel conversion, especially in the U.S.. Due to the high furnace temperature required for glass melting significant “thermal NO_x” is formed in the flame region. The rate of formation of thermal NO_x is strongly temperature dependent and approximately proportional to the concentration of nitrogen in the furnace. The conversion of an air fired furnace to oxy-fuel firing typically results in NO_x reduction by 80 to 90% as the nitrogen concentration in the furnace is reduced from about 70% in the air fired furnace to about 5 to 10% in typical oxy-fuel fired furnaces. Other key factors influencing NO_x emission are oxy-fuel burner design which influences the peak flame temperature, excess oxygen and batch nitrogen content⁶.

Melting and fining behaviors change significantly under oxy-fuel firing due to the interaction between the furnace atmosphere and glassmelt and changes in the heat transfer characteristics. The concentration of water vapor in the furnace atmosphere is about 16-18% in the air-natural gas fired furnace, which increases to 50-55% in the oxy-fuel fired furnace. Higher water vapor concentration increases water dissolution into glassmelt and enhances fining reactions⁷. Extensive laboratory studies and mathematical modeling have been conducted to investigate heat transfer, glass fining, alkali volatilization and refractory corrosion mechanisms under oxy-fuel firing. Most furnaces required some batch modifications to optimize the glass fining chemistry⁸. Although accelerated silica crown corrosion was experienced in early conversions, improved burner and furnace designs and the development of new silica crown materials with low or no lime extended the life of the silica crown close to that of a conventional air fired furnace⁹⁻¹⁰. A review paper¹¹ describes technical differences between oxy-fuel firing and the air-firing in more details.

Recent advances in oxygen production and oxy-fuel technology aim to make oxy-fuel glass melting a more cost-effective solution to meet the sustainability goal of CO₂ reduction. For example, the efficiency of air separation technology has improved and the power consumption to produce oxygen has decreased significantly. Advanced waste heat recovery technologies for oxy-fuel fired furnaces have also been developed to reduce the fuel and oxygen requirement for oxy-fuel furnaces¹²⁻¹⁴. Oxy-hydrogen combustion is considered a leading option for glass melting of future. This paper reviews the key economic factors of oxy-fuel glass melting and discusses the future of oxy-fuel combustion for CO₂ neutral glass melting.

ECONOMICS OF OXY-FUEL FIRING

The economics of oxy-fuel conversions depends mainly on the fuel savings achievable, fuel cost and oxygen cost for operating cost comparison. The value of fuel savings needs to be greater than the cost of oxygen to achieve a net saving in the operating cost when other oxy-fuel benefits such as NOx reduction and production rate increase are not considered. Many air fired furnaces less than 100 tpd capacity were converted to oxy-fuel firing as the small waste heat recovery systems, especially recuperators, are not very efficient and large fuel savings of 40-50% were achieved. For large container and float glass furnaces with efficient regenerators about 10 to 15% fuel savings have been achieved on the furnace campaign average. The economic drivers for the conversion were capital cost savings of eliminating regenerators, especially for green field projects, furnace capacity increase, and NOx reduction.

Figure 1 compares the fuel and oxygen costs for a generic 300 mtpd (metric ton per day) container glass furnace with 50% cullet and no electric boosting at three different fuel costs of 5, 10 and 15 dollars per MMBtu HHV (million Btu in higher heating value) and at a constant oxygen cost of \$50/ston (short ton). For the typical natural gas composition represented as methane, one short ton of O2 is required to combust about 12 MMBtu (HHV) of natural gas. The baseline specific fuel consumption for the air fired furnace with regenerators is 4 MMBtu/ston and fuel and oxygen savings of 10% and 30% are assumed for oxy-fuel firing without heat recovery (“Oxy”) and oxy-fuel firing with heat recovery (“Oxy-HR”) respectively. At the low fuel cost of \$5/MMBtu the baseline melting cost is \$20/ston of glass. With 10% fuel savings the specific fuel cost and the oxygen cost are \$18 and \$15 per ston of glass respectively. The combined cost of \$33 per ston is higher than the baseline cost. Even with 30% fuel savings achieved by using a flue gas heat recovery system with oxy-fuel firing the combined cost of melting increases by \$5.7/ston. At \$10/MMBtu the melting cost of Oxy-HR becomes slightly less than the air case and at a high fuel cost of \$15/MMBtu about \$5/ston savings in melting cost is projected with Oxy-HR. This example illustrates that achieving high fuel savings and reducing oxygen cost are key economic factors to make oxy-fuel glass melting as the economic choice in the future.

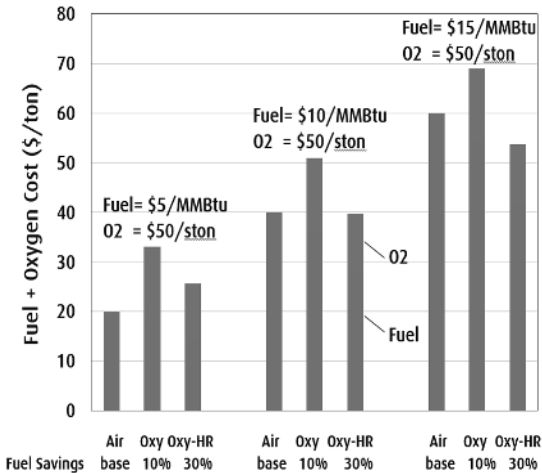


Figure 1. fuel and oxygen costs for a generic 300 mtpd (metric ton per da) container with 50% cullet and no electric boosting

OXYGEN GENERATION TECHNOLOGY

Oxygen for glass furnace conversion applications is typically supplied by the on-site oxygen generation system using a vacuum-pressure swing adsorption (VPSA) technology and backed up with delivered liquid (LOX) in a storage tank. Most of oxy-fuel fired flat glass furnaces use cryogenic air separation systems as the nitrogen co-produced from the cryogenic separation system is used for the float tank. Cost of oxygen is highly site specific and involves many factors including the plant size, electric power cost, VPSA equipment, manufacturing, construction, engineering and operation. Electric power cost is typically the most important cost element and constitutes about 1/3 to 2/3 of the overall oxygen cost depending on the power cost and the plant size. Advancements in the air separation technology have reduced the power required to separate air to make oxygen (kwh/ton O₂) over the years. Figure 2 shows a historical trend and expectation for future in a relative scale by assigning 100% for year 2019. Specific power consumption was about 40% higher in 2000. The trend is likely to continue and further improvements of 20-30% reduction are expected in the next 5 to 10 years.

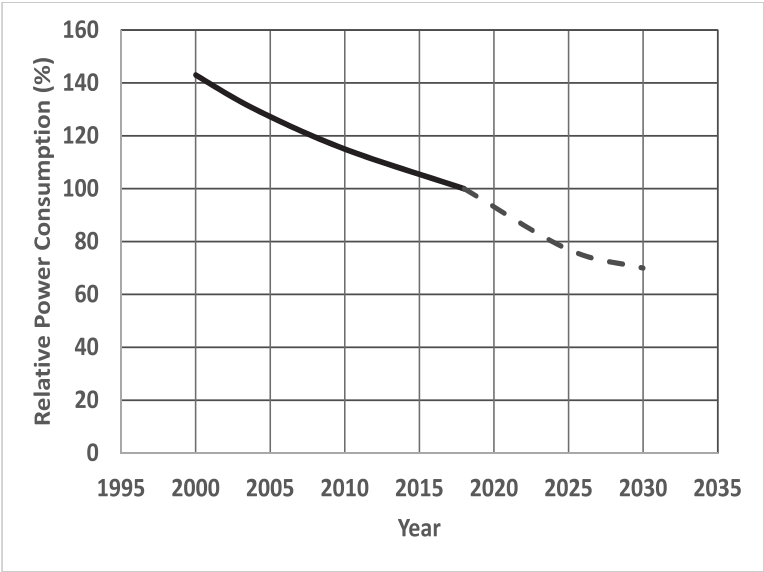


Figure 2. Historical trend of specific electric power consumption to make VPSA oxygen

ENERGY EFFICIENCY IMPROVEMENTS FOR FUTURE

In a large oxy-fuel fired glass furnace without flue gas heat recovery about 25-30% of the heat generated by combustion is lost in the sensible heat of flue gas and the balance is available in the furnace to melt glass batch/cullet and to compensate for the wall heat losses. Figure 3 shows projected improvements on specific fuel consumption for a 300 tpd oxy-fuel fired container glass furnace with 50% cullet and no electric boost. Without any flue gas heat recovery the baseline fuel consumption is 3.7 GJ LHV/t (lower heating value per metric ton or 3.52 MMBtu HHV/ston) for this state-of-the-art oxy-fuel fired furnace. The electric energy consumption for oxygen production is assumed to be 250 kWh/t O₂ generated and the primary fuel required to produce the electricity was assumed to be 9 MJ/kWh at 40% electric power generation efficiency. With the assumed primary fuel required to make oxygen overall fuel consumption becomes 4.3 GJ/t. With a full flue gas heat recovery system to reduce flue gas temperature to 250°C specific fuel consumption of 2.85 GJ/t is projected and the oxygen requirement is reduced proportionally.

Further improvements in fuel consumption requires new innovations to reduce wall heat losses and power consumption for oxygen generation. If 50% reduction in wall heat losses and 30% reduction in the power consumption for oxygen generation are achieved in the future, fuel consumption is projected to be 2.43 GJ/t without considering the fuel energy to make oxygen and 2.70 GJ/t with the assumed primary fuel for oxygen generation added. If the electric power is generated by renewable sources such as wind and solar, no fuel is required to produce oxygen. We may consider 2.5 GJ/t (2.38 MMBtu HHV/ston) as the goal for future.

Various flue gas heat recovery systems for oxy-fuel fired furnaces have been developed and installed in several commercial furnaces. They include batch-cullet preheaters, oxygen-fuel preheaters and thermo-chemical regenerators. Fuel consumption as low as 3 GJ/t has been achieved in commercial container glass furnaces¹²⁻¹⁸. Thus, good flue gas heat recovery is achievable today and the main engineering challenge is to reduce the capital costs to improve the economics. The goal of reducing wall heat losses by 50% may be more challenging with the current furnace design. Heavy insulation layers have already been applied to furnace walls and crown and the total wall thickness of hot face refractory and the insulation layers are more than 800 mm for some furnaces. Adding more insulation layers does not appear to be practical. In the typical furnace design about a third of the total wall heat losses is from uninsulated wall areas¹⁹, especially from the air-cooled metal lines. Innovative designs to reduce heat losses from uninsulated wall areas such as metal lines, skew blocks and tuck stones are required. Another design approach to reduce wall heat loss per ton of glass is to design a rapid melting system with very small total wall areas. The maximum pull rate of the current container furnace design is about 4 tpd/m², often assisted with electric boost. If the specific pull rate is increase to about 10 tpd/m², then the total wall area would be reduce to about ½. In a pilot scale test of a rapid melter with oxy-fuel roof fired burners melting rates as high as 25 tpd/m² have been demonstrated by operating the furnace temperature above 1700°C²⁰. A pilot scale rotary glass melting furnace with spray water cooled wall was demonstrated to withstand the very high furnace temperature²⁰. Submerged combustion melter with water cooled walls is another approach to rapid melting²¹. Although water cooled walls have very high specific heat loss, small wall area may make the total wall heat losses less than that of the current furnace design.

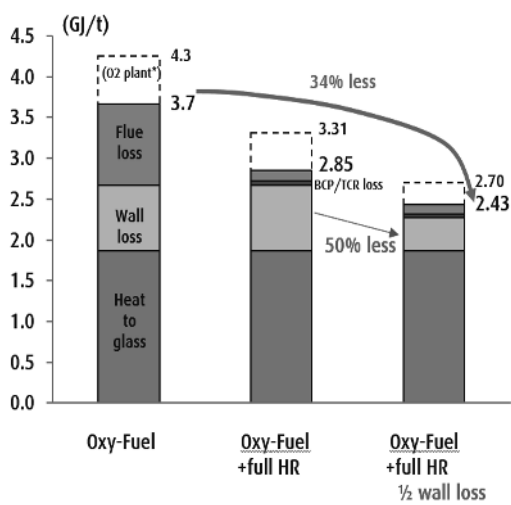


Figure 3. Potential improvements in specific fuel consumption for a 300 mtpd container furnace with 50% cullet.

CURRENT CO₂ EMISSIONS FROM GLASS PRODUCTION

Figure 4 compares CO₂ emissions from a 300 tpd container glass furnace with 50% cullet using 1,000 kW of electric boost. Specific fuel consumptions assumed are 4.0 GJ/t for air firing, 3.8 GJ/t for oxy-fuel firing (“OXY”), 3.1 GJ/t for oxy-fuel firing with heat recovery (“OXY-HR”), and 800 kWh/t for full electric melting²¹. The CO₂ emission from decomposition of soda ash and limestone/dolomite in the batch contributes about 100 kg/t for each case. CO₂ emission from natural gas combustion contributes about 210 kg/t for the air fired furnace, 200 kg/t for OXY and 160 kg/t for OXY-HR. CO₂ emissions from electric power generation range from zero for renewable power such as wind and solar to as high as 1.0 kg/kWh from an old coal fired power plant. The average CO₂ emission in the U.S. was about 0.5 kg/kWh in 2015 and about 0.4 kg/kWh in EU in 2011. In this analysis CO₂ emission rate of 0.4 kg/kWh was assumed. 1,000 kW of electric boost contributes 32 kg/t of CO₂ emission. The electric power required for oxygen generation also contributes to the overall CO₂ emission. At an assume electric power requirement of 250 kWh per ton of oxygen generation additional CO₂ emissions of 29 and 23 kg/t come from OXY and OXY-HR respectively. For the full electric melter with 800 kWh/t of power consumption CO₂ emission becomes 320 kg/t and the total CO₂ emission 420 kg/t, which is higher than those from the natural gas fired furnaces by about 15 to 35%.

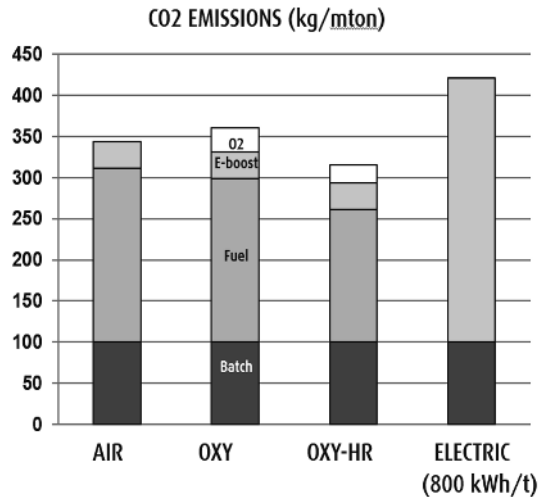


Figure 4. Comparison of CO₂ emissions from 300 tpd container glass furnaces at 50% cullet

In order to achieve 90% reduction in CO₂ emissions in the future all these sources of CO₂ emissions have to be substantially reduced. Raw materials have to be mostly free of carbonate materials such as cullet. For container glass manufacture cullet ratios as high as 90% are already used in some furnaces and the trend for higher cullet uses will continue. Electric power has to be either generated from renewable sources or nuclear plants and CO₂ emissions from fossil fuel burning power plants have to be captured and sequestered. For fuel fired glass melting furnaces biomass derived fuels or hydrogen made without CO₂ emissions need to be used.

HYDROGEN AND BIOMASS DERIVED FUELS FOR REDUCING CO₂ EMISSIONS

Hydrogen is considered as the fuel of future to eliminate CO₂ emissions from combustion of hydrocarbon fuels. Large scale demonstration projects have been announced in EU. For example, existing natural gas distribution pipelines are proposed to be converted to distribute compressed hydrogen in Leeds, UK²⁴. On a volume basis hydrogen has a lower heating value (LHV) of 10.8

MJ/Nm³ @ 0 C (275 Btu/scf @ 60F) as compare with 35.8MJ/Nm³ (913 Btu/scf) for methane. For the same heat input the volume flow rate of hydrogen becomes 3.2 times greater than that of methane or typical natural gas. For oxy-fuel combustion hydrogen has an advantage over natural gas as the oxygen requirement for combustion to generate the same amount of heat (LHV) is reduced by about 17%. Hydrogen has a wider flammability range and a higher adiabatic flame temperature as compared with methane. For glass furnace combustion applications hydrogen flame is non-luminous, but the radiation heat transfer is excellent because the water vapor concentration of combustion gases is near 100%, which enhances gas emissivity of oxy-hydrogen flame and combustion gases. The conversion of the existing natural gas firing system to hydrogen firing requires fuel piping and burner modifications, but no fundamental heat transfer issues are expected with a proper oxy-hydrogen burner design. As experienced in the conversion of air-fired furnace to oxygen firing, higher water vapor concentration in the furnace atmosphere is expected to increase the water dissolution into glassmelt and to enhance the fining reactions⁷⁻⁸. Reduction of batch fining agents is recommended²³ to compensate for the enhanced fining reactions and to control foam generation.

Table 1 compares hydrogen and biomass derived fuels with natural gas (as pure methane) for glass melting applications²⁵. For each fuel specific fuel and oxygen consumptions were calculated for a typical 300 mtpd container furnace with 50% cullet and compared. The baseline specific natural gas and oxygen consumptions were 3.87 GJ/t and 220 Nm³/t respectively. Approximate fuel costs are also compared assuming \$8/GJ LHV for natural gas which was a typical cost in EU in 2018. Most of hydrogen used today is made from natural gas by the steam-methane reforming (SMR) process. Typical hydrogen yield is about 70% based on the lower heating value of hydrogen (LHV) as compared with the LHV of natural gas input. The cost of hydrogen made from natural gas is roughly twice that of natural gas and assumed to be \$15/GJ. The cost of CO₂ capture and sequestration (CCS) from the SMR process is not included. Both hydrogen and oxygen can also be made by the electrolysis of water using renewable electric power. According to a report by IEA²⁶ the project cost of hydrogen in 2030 made by electrolysis is about \$2 to \$4 per kg of H₂ as compared with about \$1.4 to \$3 per kg of H₂ made from the SMR process with CCS. The large variations are mostly due to regional variations in the renewable power cost and the natural gas cost. The specific fuel consumption with oxy-hydrogen firing increases by about 1% as compared with oxy-methane firing and the specific oxygen consumption is reduced by 15%. The main challenge of using hydrogen for glass melting is its projected high cost. As shown in Figure 1 oxy-fuel firing is likely to be more favored than air firing at \$2 per kg of H₂. (\$2 per kg of H₂ corresponds to \$16.7 per GJ LHV or \$17.6 per MMBtu LHV).

Digester gas is produce from anaerobic digestion of organic materials such as pig and cow manures and municipal waste water sludge. Typical composition is about 60% methane and 40% carbon dioxides by volume. The existing natural gas firing system can be modified to fire compressed digester gas. Both the specific fuel and oxygen consumptions are projected to increase by 10%. Digester gas is typically priced less than natural gas and assumed to be \$6 per GJ, but the availability is limited to the proximity of local digesters. Liquid fuels produced from biomass include ethanol and pyrolysis oil. Biomass based ethanol is produced from corn, sugar cane and other crops in large quantities for gasoline blends. In the U.S. over 1 million bbl/day of corn ethanol was produced in 2017. It is enough to produce 400 million tpy of container glass at 4 GJ/t, which is more than three times the world container glass production. Fuel and oxygen requirements are similar to the natural gas fired system. Although the existing natural gas firing system can be

modified to fire ethanol, high cost of fuel is the major hurdle at present. Pyrolysis oil is produced from wood and other biomass by a thermal decomposition process optimized to produce liquid products containing various oxygenated hydrocarbon compounds and water. Heating value is about 16 MJ LHV/kg with 25% water content corresponding to about 60% of LHV of ethanol (27.7 MJ/kg). When fired with oxygen about 20% more heat input is required as compared with natural gas.

Table 1. Fuel and oxygen consumption and cost of biomass derived fuels relative to natural gas for an oxy-fuel fired 300 mtpd container furnace at 50% cullet without electric boost

	SPECIFIC FUEL CONSUMPTION (%)	SPECIFIC OXYGEN CONSUMPTION (%)	APPROXIMATE FUEL COST (\$/GJ in EU)	APPROXIMATE FUEL COST (\$/T GLASS in EU)
Natural Gas	100	100	8	31
Hydrogen	101	85	15	58
Digester Gas	110	111	6	26
Ethanol	102	97	18	71
Pyrolysis Oil	121	127	8	38
Dry Wood	119	117	8	37
Torrefied Wood	100	88	9	35

Solid fuels such as wood chips, wood char and torrefied wood can be fired with oxygen in glass furnaces. Since pulverized petroleum coke has been used in glass melting furnaces, there is no fundamental technical barriers to use solid biomass fuels as long as ash quality is compatible with the quality of glass produced. Solid fuel firing, however, requires a pulverization step and a special solid fuel feeding and distribution system and the conversion from a natural gas fired system is more involved. Dry wood with 5% moisture requires about 20% more fuel and oxygen as compared with natural gas. Torrefied wood is produced in a mild roasting process and is an excellent dry fuel. Fuel requirement is the same as natural gas and the oxygen requirement is reduced by about 12%.

SUMMARY

Over 300 oxy-fuel fired glass melting furnaces operate worldwide today and provide the benefits of fuel reduction, productivity increase and NOx reduction. For wider adoption of oxy-fuel firing the reduction of fuel and oxygen consumption and the cost of oxygen generation is required. Several oxy-fuel fired furnaces have been equipped with flue gas heat recovery systems and specific fuel consumption as low as 3 GJ/t (2.8 MMBtu/ston) have been demonstrated in container furnaces. The goal of 2.5 GJ/t (2.4 MMBtu/ston) is considered to be technically feasible with 50% reduction in wall heat loss combined with flue gas waster heat recovery. For CO2, neutral glass melting of future

hydrogen and biomass derived fuels can be used with oxygen for glass melting. There are no major technical barriers in using hydrogen for glass melting and oxygen-firing is likely to be favored over air-firing due to expected high hydrogen costs and the reduced specific oxygen requirement with hydrogen combustion.

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