Reducing emissions with GLASS SERVICE's advanced new furnace

During the upcoming Glass Service conference in June 2023, which is held every two years, glass producers and suppliers present the latest developments and discuss the results and reliability of furnace models. It is quite logical that no glass producer will build a new furnace concept melting 300+ tons per day without thorough analysis, calculations and extensive CFD modelling - something Glass Service has already been doing since its founding in 1990. The company has developed GS-GFM, a leading Glass Furnace Modelling Software. GS GFM is currently licensed to 35 glass producers and leading suppliers, with about 1000 solvers now licensed. Glass Service has performed about 1000 furnace design and optimization studies in-house. Lately most of these are asking how to reduce carbon emissions by increasing the amount of either electric melting or hydrogen. Such intensive use of CFD modelling was already seen when Oxy-fuel applications emerged, and now with the next generation of large Hybrid (with more than 50 percent electric boosting) or all Electric melter, another increase can be seen.

This year the main topic at GLASS SERVICE's sixteenth International Seminar on furnace design, operation and process simulation will be that of working out how the company can reduce its carbon emissions by way of new furnace concepts and ideas - all safely developed and tested by using Computational Fluid Dynamics (CFD) modelling.

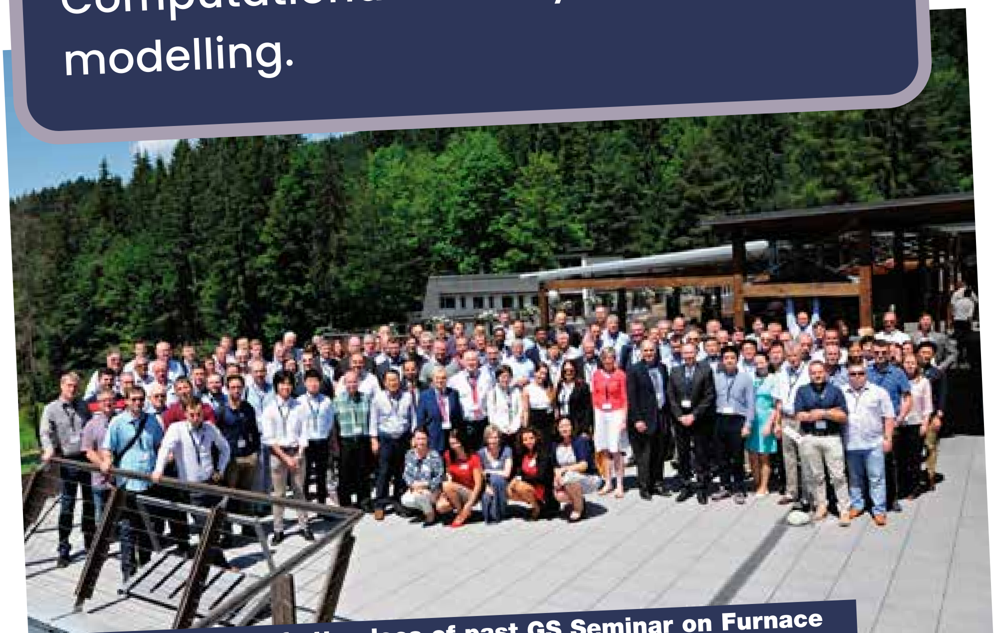

Figure 1. Photo of attendees of past GS Seminar on Furnace design, operation and process simulation

Besides the main seminar there will be separate meetings of ICG Technical committee 15&21 on Furnace design and operations, as well as a GS GFM Users meeting and a high level glass defect workshop.

Glass plays an important role in our society. Its usage in housing, transportation, communication, food storage, etc. is crucial to enjoying a high quality of life. Glass production requires both raw materials and energy. Reducing dependency on the need for materials is possible through further recycling. Indeed a significant advantage of glass is that it can be endlessly recycled without loss in quality or purity - even if glass waste needs to be purified, cleaned, and colour separated before use.

Using more cullet for melting means not only considerable savings in raw materials costs and energy usage, but CO_2 emissions are also lower. Clean cullet needs to be reheated and homogenised; but melting reaction energy is not required and every ten percent cullet addition reduces the energy consumption of glass melting by two to three percent. To melt soda lime glass from raw materials requires energy of about 2.6 MJ/kg. As pure cullet, this is reduced to 1.9 MJ/kg. More importantly, re-melting cullet avoids CO_2 emissions from soda ash (Na_2CO_3) and lime ($CaCO_3$) in the batch. Every metric ton of waste glass recycling saves about 315 kg of CO_2 that would be released manufacturing a new glass product. The most common, efficient, end-fired, container glass furnaces, melting with an average of 50 percent cullet, consume about 3.5 MJ/kg.

Melting glass requires considerable energy to reach the necessary high temperatures (>1500°C). Glass production used to take place in 'glass houses' where people had local resources - sand and wood ash as raw materials and wood from the forest for energy. Old glass houses can still be found in forested areas. As much as 150-200 kg of wood was needed then to melt a kg of glass [4]. Assuming wood burning generates about 19 MJ/kg, this equates to >2850 MJ for a kg of glass. Today's result of 3.5 MJ/kg is astonishingly 800 times more efficient.

Over the last century, the main energy source has shifted to fossil fuels such as oil and natural gas. Modern glass melting uses about 1 percent of all industrial energy much less than for example steel production. Nevertheless, it is energy intensive and massive improvements have been made over the years.

Furnace efficiency has increased because new refractories allowed higher combustion and crown temperatures, and increased melting temperatures. Furnaces became larger, producing more glass per m2 of heat loss surface. Some flat glass furnaces now produce a remarkable 1200-1500 tons/day while container glass furnaces can melt a high 800 tons/day. But furnace size is limited by the maximum crown span (width), the size of equipment, flame length, and other factors. Larger regenerators have increased heat regeneration from 50 percent to 70 percent, close to the theoretical maximum of 75 percent. This maximum arises from the difference in heat flow in the waste gas (greater mass and specific heat) than the air being preheated.

Figure 2 shows the design of the most common U flame (end-

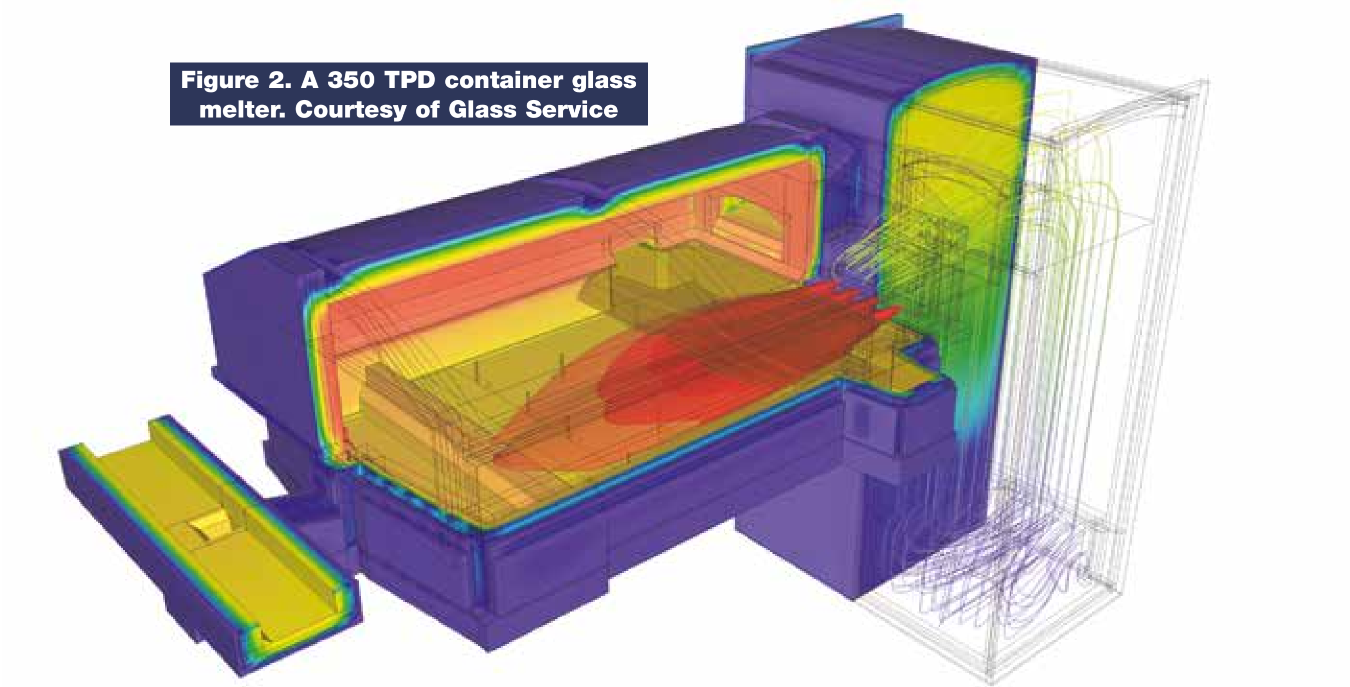

Figure 2. A 350 TPD container glass melter. Courtesy of Glass Service

fired) container glass melting furnace, producing about 350-380 TPD (tonnes/day). Cold air enters the base of the regenerator at the right and is preheated to 1200-1300°C, before leaving at the top and entering the combustion chamber. Gas (or oil) is injected into the hot air at the base of the port. This example has four injectors. The iso-temperature surfaces indicate the flame shape that develops. The hot gases radiate heat to the glass melt surface, the furnace walls and the crown, the latter two re-radiating energy to the glass. The waste gases then circulate round the furnace and exit via the left exhaust port, entering the opposite regenerator, and preheating it until the process is reversed after 20-30 minutes. Raw materials enter into the melting basin from two sides. First the batch under the flames is melted. Some designs have a barrier wall (0.8 m high) on the bottom of the furnace to bring the glass from a typical depth of about 1.3 m to the melt surface to aid the removal of small bubbles, the so-called fining process. The glass then dives down into the sunken throat to be delivered into the distributor which connects to the forehearth which takes the glass to the forming machines. The small rods protruding from the bottom of the glass basin are molybdenum electrodes that assist in melting the glass by electrical Joule heating, often called electric boosting. Such a melter is typically about 15 m long by 6 m wide.

The second most common glass melter is the cross-fired regenerative float glass furnace. Flat glass is formed after leaving the melter by floating the melt on a molten tin bath. This glass is mainly used for window glass or automotive windshields also solar panels or sometimes LCD products can be produced. The furnaces can be 35-40 m long and 10-12 m wide. The most typical pull rate is 600-800 TPD, but some furnaces produce 1200 or even 1500 TPD. These cross-fired regenerative furnaces alternate firing from opposite sides. They have five to nine burner ports on each side and the preheated air comes from brick regenerators on each side. Injectors introduce gas into preheated air to create flames crossing the glass melt surface, the hot waste gases exiting to the opposite regenerators. This process is reversed about every 30 minutes. Figure 3 shows a 600 TPD float furnace with 5 ports with 2 gas injectors on each side. Raw materials are introduced by batch chargers. After melting, the glass is cooled in the working end and then leaves via the canal onto the molten tin, where it spreads out to form a flat sheet.

OTHER FURNACE DESIGNS

Other technologies include the recuperative and the oxy-gas furnace. Oxy-gas furnaces use pure oxygen, extracted from air and may seem more energy efficient than the best regenerative furnaces. However any correct analysis would require the energy and cost of separating the oxygen to be considered and would usually favour a regenerative furnace. That said, oxy-gas furnaces can bring other benefits, including NOx reductions and a smaller footprint. Recently, two industrial gas suppliers have reduced energy consumption by preheating the fuel and oxygen.

Linde (Praxair) developed the OptiMeltTM technology to save another 20 percent of energy by preheating the natural gas with waste gas from the oxymelter to create a syngas (CO + H_2) formed by cracking CH_4 with CO_2 in the waste gas. An interesting side benefit is that CO tends to reduce foam on the glass surface, increasing heat transfer and lowering seed counts.

Air Liquide designed HeatOx technology with heat exchanging recuperators using furnace waste heat to preheat the natural gas and oxygen indirectly to 400-500°C, giving 9-10 percent additional energy savings. Should

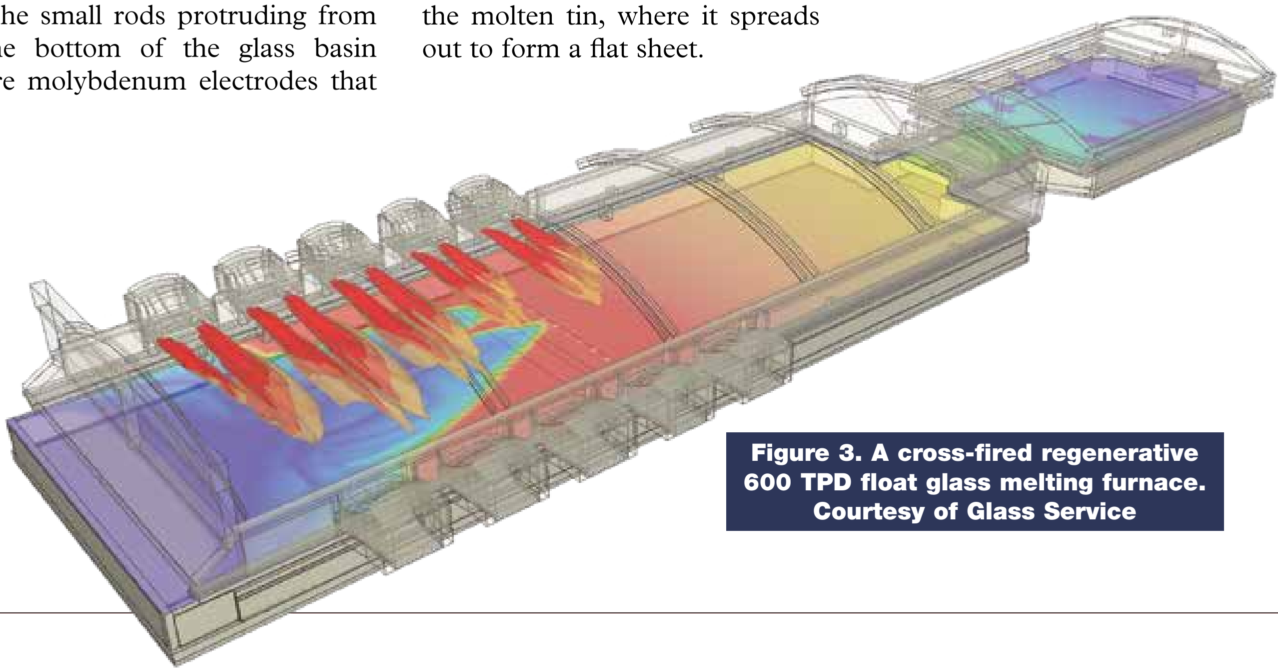

Figure 3. A cross-fired regenerative 600 TPD float glass melting furnace. Courtesy of Glass Service

this technology be installed in a conventional regenerative float furnace converted to oxy-gas firing, a total of 20-25 percent energy savings may be achieved. A side effect would be a major NOx reduction.

Finally an oxy-gas furnace is apparently converted to burn hydrogen more easily than an air-fired furnace. Burning hydrogen with air gives higher flame temperatures typically equated with higher NOx emissions. Oxy-gas furnaces may therefore be more attractive when hydrogen is affordable.

ELECTRIC MELTING

The first continuous regenerative glass melting furnace was invented by Charles William Siemens of Westminster England between 1872 and 1880 and modern regenerative furnaces have changed little since.

Many do not realise though that continuous all-electric melting (AEM) is almost as old as gas-fired regenerative melting. The first electric furnace was built in 1905 following French Sauvageons design and was for window production. The specific energy consumption was even then only 0.73 kWh/kg. Many designs have been implemented since then, though electric melting recently became unpopular due to its high cost compared to widely available fossil fuels.

Global warming and pressure on carbon footprints, has rekindled interest in full or partial (hybrid) electric melting. Alternative energy sources for electricity have helped to lower costs and production is essentially CO2 free; for example in Germany, 40 percent of electricity is generated using renewable resources such as wind, solar, hydro, and bio. The question for the future is not if more electricity will be used for glass melting but what will be the balance between fully electric and hybrid furnaces (substituting bio fuel for fossil fuel).

Glass is important in generating green renewable energy, or 'green electricity'. Most wind turbine blades are composed of reinforced glass fibre. And most solar panels use large quantities of flat glass. In the future photovoltaics will probably be widely integrated into windows. These applications mean that glass is not only a consumer of renewable energy. It also has an important role in generating it.

For larger furnaces with higher pull rates, the higher volumes and lower wall losses make recuperators or regenerators sensible. Gas-fired furnaces can be cheaper than the efficient electric melter. This was historically so in most countries because electricity was generated from fossil fuels, and typically 2.5 to 3x more costly per kWh than the fuel alone.

Even small electric furnaces are 70-85 percent thermally efficient. While a fuel fired furnace without a recuperator at a low pull is only ten percent efficient, adding a regenerator improves efficiency to 45 percent and an oxy-gas fired furnace can achieve 50 percent efficiency.

Most common all-electric melters produced 10-30 TPD, sometimes up to 80 TPD. They were round or hexagonal to avoid heat losses via the furnace walls and to allow more easily distributed batch charging and electric connections. Figure 4 shows a larger rectangular melter at 80 TPD. These cold top electric melters used the batch cover as a heat insulating blanket, conserving heat inside the melt. They were called vertical melters, as the glass melts on the surface near the batch, refines at lower levels and flows out via a bottom throat into a working end/distributor. To maintain batch coverage and hence an insulating blanket, the cullet content was usually below 50 percent. Electric melters were mostly used for high quality clear glasses and crystal (lead) glasses, as the redox (colour) control is best managed with this process.

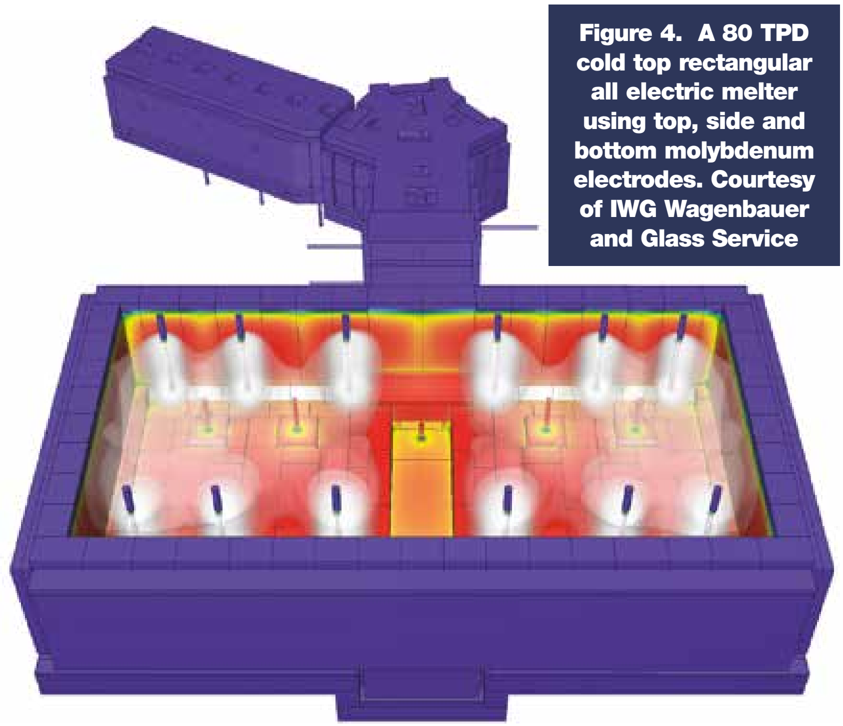

Figure 4. A 80 TPD cold top rectangular all electric melter using top, side and bottom molybdenum electrodes. Courtesy of IWG Wagenbauer and Glass Service

During the 1970 global oil crisis, some glass producers, especially in the United States converted all their regenerative furnaces into electric melters. They retained the infrastructure and horizontal configuration because other shapes were difficult to incorporate into their existing space; sidewall losses are less important at higher pull rates.

THE FUTURE OF CARBON FREE MELTING – ELECTRIC, HYDROGEN OR HYBRID?

Currently, 95 percent of all glass melting uses fossil fuels, mostly natural gas or heavy oil; but industries are now strongly encouraged to follow the Paris Climate Agreement guidelines and are seeking to minimise CO2 emissions. Many but not all countries are enforcing rules, with penalties for carbon emissions and benefits for reductions. Either way, the glass industry knows its consumers expect low-carbon or carbon-free production, so are working to achieve this while remaining competitive amongst themselves and with other packaging materials.
Four key technologies for carbon reduction exist, in addition to those already discussed. These are:

1. Cold top all electric vertical melting (AEM)
2. Hydrogen combustion (replacing natural gas in regenerative or oxy-gas furnaces)
3. Horizontal hot top electric melting (H2EM), also referred to as hybrid melting
4. Horizontal hot top hydrogen electric melting (H3EM)

The question is: What is the best solution - not just now, but for 2030? 2050? After 2050?

HYDROGEN

Currently, truly green hydrogen produced by electrolysis using renewable electric energy is the first choice, but there is simply not enough available. Even with low electric pricing, hydrogen at 6€/kg is three times too costly to compete with natural gas. So, in most regions it would be uneconomical without a state subsidy. More research on hydrogen combustion is needed, specifically the effect on the molten glass and refractories of water concentrations approaching 100 percent in the combustion atmosphere. Certainly concentrations near 50 percent in the combustion atmosphere of oxy-gas furnaces created problems. Using electricity to break water into H2 and O2 by electrolysis is expensive and is only now reaching 70 percent efficiency levels. However, expectations are that investment costs should decline while efficiency continues to increase so that, as more renewable electricity becomes available, hydrogen will become affordable.
But why consider hydrogen? If electricity is used directly, the furnace melting efficiency is much higher than via the hydrogen route. An advantage of hydrogen is the possibility of storage for long periods, allowing long-distance transportation and creation of a buffer against supply hiccoughs. Storing electricity for similar times is simply not efficient. Unused batteries slowly lose power, while storing sufficient energy would require huge batteries. Different storage options are shown in Figure 5; some, such as hydropower, have been created but are not universally applicable - mountains and water reservoirs, as in Norway or Austria, being necessary. Energy

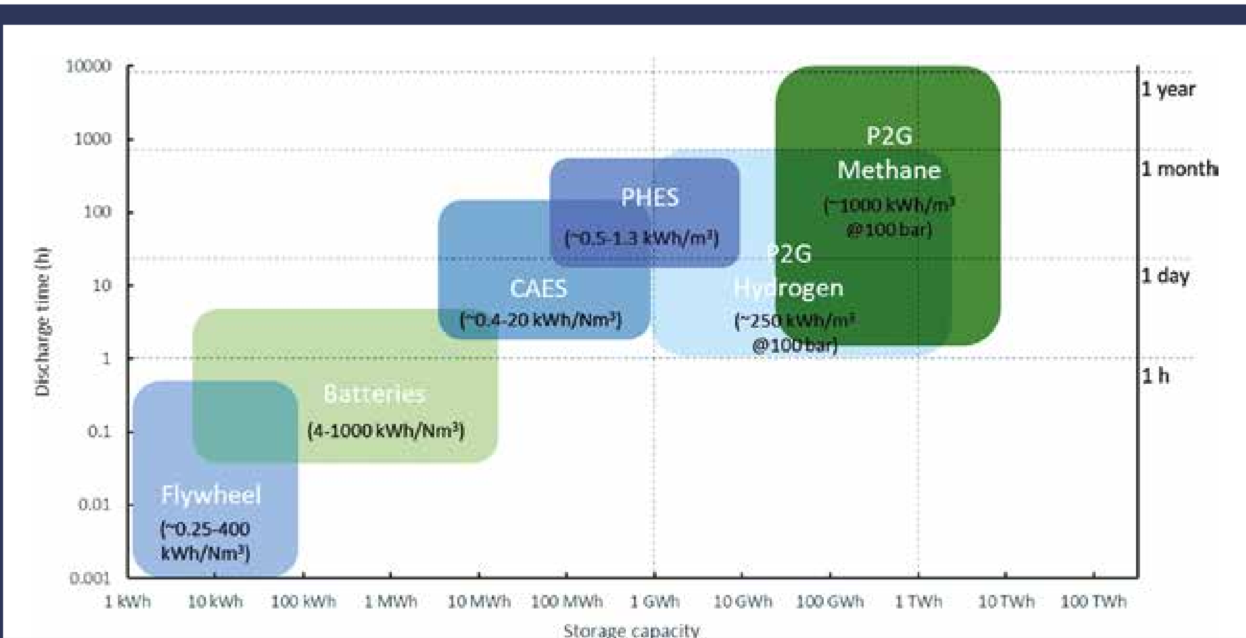

Figure 5. The capacity and discharge times for different storage technologies. Source RMIT

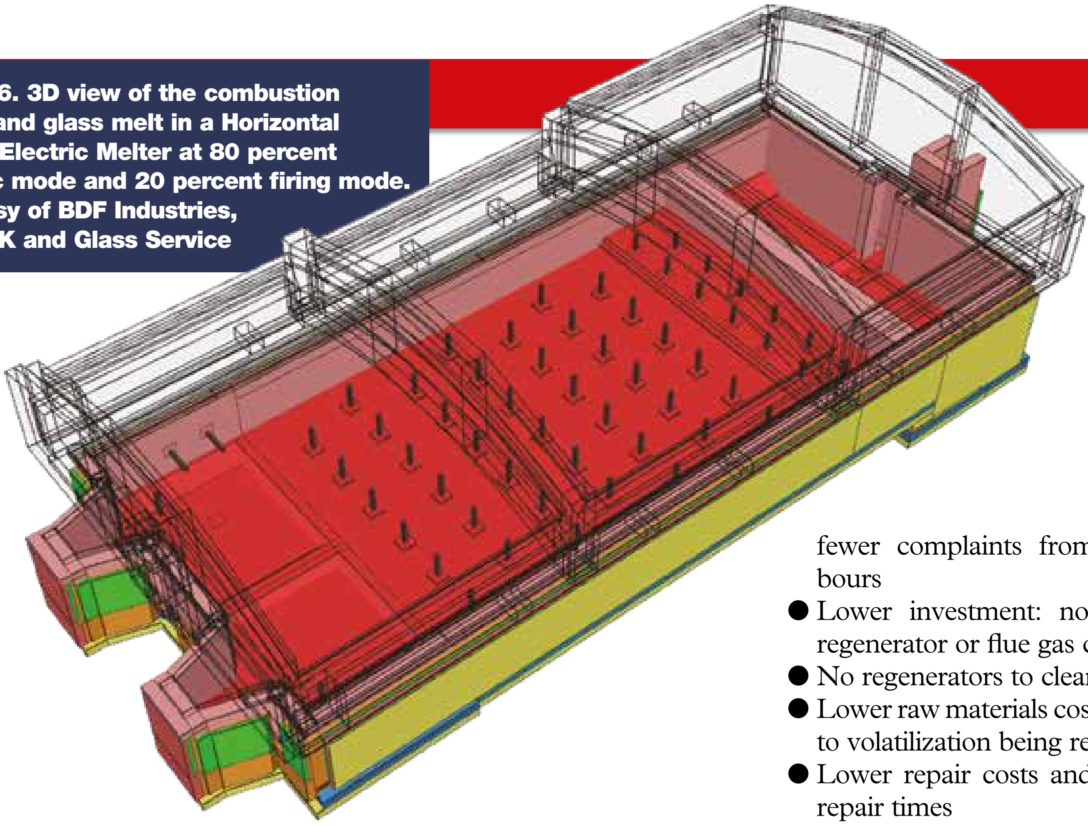

Figure 6. 3D view of the combustion space and glass melt in a Horizontal Hybrid Electric Melter at 80 percent electric mode and 20 percent firing mode. Courtesy of BDF Industries, F.I.C. UK and Glass Service

storage today is facilitated by methane which can be stored for millennia in caves with appropriate geology.

FlammaTec (part of GS Group) developed a Hydrogen burner for glass melting in 2018.

ALL-ELECTRIC MELTING

Electric melting has been a proven technology for over a century, so why not convert all furnaces to all-electric melting? Mainly because electricity typically costs three times as much for natural gas/kWh. While electric melters are twice as thermally efficient, they are more expensive to operate. Another obstacle remains. Most electric melters are producing less than 80 TPD. Only a handful in the entire world melt more than 100 TPD; and only two have produced 200 TPD - both were stopped due to production issues. All-electric melters greater than 200 TPD have diameters so large that maintaining a well-distributed insulating batch blanket across the melt surface is difficult although a key requirement for keeping the furnace operational. Should the batch cover disappear, the furnace loses heat from the top, the glass cools, melt quality and pull rate fall and production deteriorates. There is also limited long-term experience at that size of producing reduced coloured glasses or melting with high cullet levels.

HYBRID MELTING

Hybrid melting entered the glass dictionary in 2017, being mentioned by companies such as Glass Service, FIC, BDF Industries, Fives, Teco, Horn and Sorg. Previously discussion was limited, though hybrid melting simply means more than one heat source and has a long history. It is analogous to hybrid cars where the engine is the main power source, while the battery-driven electric motors can move the car short distances and add extra power during acceleration. Previously, electric boosting in glass production was often for 15-30 percent of the total energy input. Combustion is also used in hybrid melters (H2EM), but 50 percent or more energy comes from electric heating. The thermal efficiency of the electricity is 85-90 percent, while combustion is about 50 percent.

A smaller all-electric furnace (<4 TPD/m2) has the following advantages:

- No emissions (NOx, SOx) or particulate dust, so no filter or cleaning costs for waste gas
- No chimney stack and therefore fewer complaints from neighbours
- Lower investment: no crown, regenerator or flue gas channels
- No regenerators to clean
- Lower raw materials costs owing to volatilization being reduced
- Lower repair costs and shorter repair times
- Efficiency is less impacted by furnace size and capacity

Common disadvantages are:

- Less pull rate flexibility
- Shorter furnace lifetime (eight years for smaller furnaces 50-80 TPD)
- Limited experience of operators
- Dependent on electrical power stability)
- Proven melting only up to 55 percent cullet
- Limited experience with producing reduced coloured container glass (hybrid melting helps)

Hybrid melting removes some disadvantages:

- Shorter furnace lifetime (10-12 years)
- Less experience of operators (behaves more like a standard furnace)

Glass Service and FIC in cooperation with BDF Industries developed a Hybrid design in 2017. A flexible design independent of energy source, melting at times with 80 percent fossil fuel/H2 and 20 percent electric boost (at 3 MJ/kg), or conversely 80 percent boost and 20 percent combustion (at 2.5 MJ/kg). This should reduce the risks of adopting a new technology. Figure 6 shows the concept design of such a horizontal hybrid electric melter for container glass.

Renewable source	Electricity	Hydrogen electric	Hydrogen combustion
Renewable source	100%	100%	100%
Electrolyzer		70%	70%
Compressor		92%	92%
Transportation	92%	98%	98%
Transformer/fuel cell	95%	52%	
Heat losses effect (electrode holders, fluegas)	90%	90%	45%
Total	79%	30%	28%

Table 1. Comparison of electric melting efficiency versus hydrogen route

Hybrid electric melting and oxy-gas furnaces such as this one can break the magic energy barrier undercutting a specific energy consumption of 3 GJ/ton of glass (with 70-80 percent cullet).
Table 1 shows that using electric energy directly in the glass melt is much more efficient than hydrogen - whether by combustion or via the fuel cell. Direct efficiency is estimated to be 79 percent, whereas hydrogen reduces efficiency below 30 percent.
In float glass production it will also be possible to use much more electric heating or super boosting than what was common till now. A design by FIC UK which makes some first steps into this direction is shown in figure 7 with a 6 MW bottom melter boost installed in a conventional regenerative float furnace. To make the complete transition it may be more interesting to combine this also with oxy combustion and then at some point replace the natural gas to more Hydrogen and waste heat recovery. But the efficiency route using Electricity directly will always be higher.

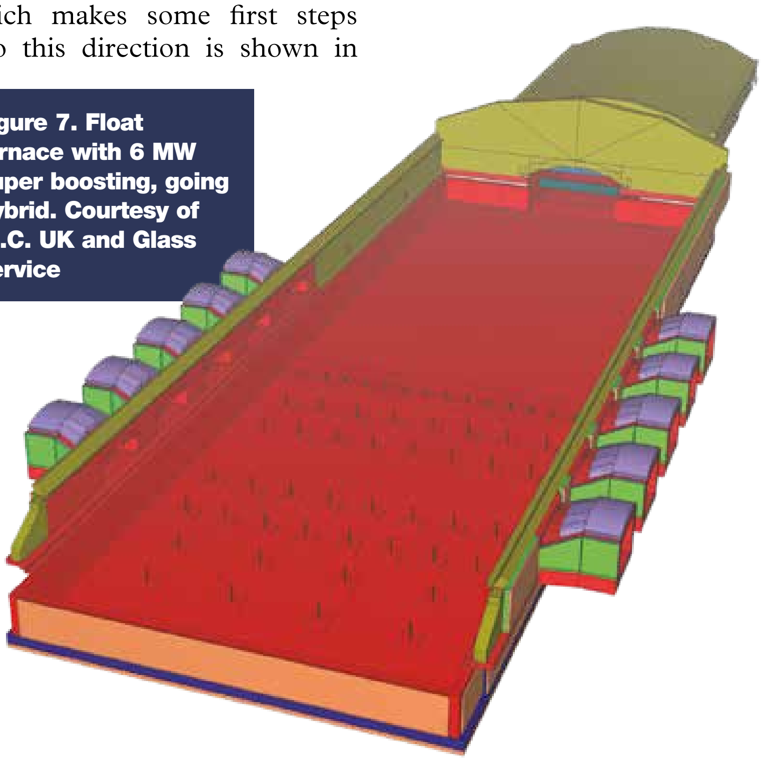

Figure 7. Float furnace with 6 MW Super boosting, going Hybrid. Courtesy of F.I.C. UK and Glass Service

CONCLUSIONS AND OUTLOOK

With the help of Industry 4.0 automation & renewable energy sources, the required 55 percent reduction of carbon emissions should be possible before 2030 through

- Improved glass recycling (in both amount and quality)
- Improved Model Based Predictive Furnace control (Dynamic balancing of Electric vs Combustion firing)
- Greater use of low-cost green electricity, in hybrid or all-electric furnaces, and
- the use of hydrogen for combustion or electricity generation.

Generating hydrogen using green electricity will become important after 2030. The 2050 goal of an 80 percent CO_2 reduction will require large amounts of green electricity and a functioning hydrogen economy that can replace fossil fuels for glass production, as well as transportation to and from the factory. ■