9.7

Design and Operation of Glass Furnaces

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1   Introduction

To a large extent, the history of glassmaking is that of melting furnaces. Throughout the ages, the course of the reactions between the raw materials largely determined quality as well as production volumes and cost. Thanks to the new science of thermodynamics, the major improvements progressively brought in the nineteenth century resulted in the invention of the *regenerative tank* furnace (Chapter 10.9). Not only were then melting temperatures higher and more uniform, but heat hitherto wasted was recovered while continuous instead of batch melting ensured the much higher throughputs, more durable equipment, and lower labor costs that have since then sustained the expansion of the glass industry.

Modern furnaces are typically from 8 to 40 m long, 5–15 m wide, and hold enough glass over typical depths of 0.9–1.4 m to ensure a daily production ranging from 20 to 700 tons with extreme pulls exceeding 1000 tons for a total investment cost ranging from about 2 to 15 M€ as of 2019. These furnaces of course differ from those designed by the Siemens brothers and other nineteenth-century engineers, but the basic goals involved have remained the same, namely to save as much energy as possible and to deliver continuously at the best cost a homogeneous melt ready to be shaped. The main changes have been: (i) the switch from coal to natural gas, heavy oil, or electricity as a heating source; (ii) the nature of the refractories used for the tank, combustion space, and preheating chambers [1], which have much benefited from advances in the technology of ceramics and other relevant materials; (iii) the precise tailoring of a furnace in terms of the energy sources available, targeted pull rate

(and possibly intended variations), kind of production and raw materials used, cullet included (Chapter 9.9); (iv) the manner in which the geometry of the tank and its temperature distribution are designed to optimize melt homogenization and fining by the currents generated by the free convection caused by temperature and density differences, the exerted pull, and possible bubbling and electrical boosting; (v) and increasingly strict environmental regulations in terms of emissions of CO_2 and pollutants, particular emphasis being put on sulfur and especially nitrogen oxides (SO_2, SO_3, NO, NO_2, N_2O, and their derivatives), which are generically denoted by SO_x and NO_x, respectively.

Like in any complex industrial production, changes in the various chemical and physical factors involved may have opposing effects in the technical optimization of the overall process as well as on fabrication costs. Compromises have thus to be found, which is why a given furnace will be adequate for a given use at some place but not for others elsewhere. This is also why a new furnace still requires much experience from its designer in spite of the wealth of information that can now gathered a priori from computer simulations of the whole melting operations (Chapters 1.7 and 9.8).

To review these various features in this chapter, a brief overview of furnaces will first be provided through their *hearts* (the melters) and *lungs* (the regenerators) and of the five main types of heating systems. The fusion process itself will not be addressed because it has already been described in Chapter 1.3. A more detailed description of the tank and superstructure of melters, of the regenerators, and of their ancillary equipment will then be given, interest being paid to the nature of the refractory materials used whose resistance to corrosion and thermal shock are critical in any respect [2]. Finally, some general considerations about furnace design will be reviewed before the issue of pollutants emitted such as NO_x will also be

considered in view of the ever stricter nature of environmental regulations.

In contrast to forming processes, which are mainly determined by the kind of production (e.g. float process for window glass), melting of the batch can be made with different types of furnaces for the same production. More than elsewhere in the Encyclopedia, economic factors will thus form the backdrop to the present chapter. From this standpoint, a basic figure is the specific load, which is the amount of glass daily produced by surface area of the melter: the production (in tons per day, tpd) is then derived at once from it and the melter surface. As illustrated by the fact that melting alone represents 60–70% of the overall energy spent in glass production [3], the energy efficiency is another fundamental notion to which another chapter is devoted (Chapter 9.8). In view of the introductive nature of the present account, interested readers are referred to standard treatises for more detailed descriptions (e.g. [4]).

2 The Furnace Families

2.1 Common Features

Glassmaking furnaces are generally not specific to a given type of production because their operations depend on so many factors that they can be optimized in different ways and adapted to particular features of the glass produced (e.g. fluor volatilization in opal glass, low thermal expansion of borosilicates, high Fe content of rock wool). In contrast, their sizes depend on the subsequent forming process because they are mainly determined by the desired pull rate. This is the obvious reason why the biggest are those designed and built for float glass (Chapter 1.4).

The most conspicuous part of a furnace is the melting tank (Figure 1). It is fed with the raw materials coming from the outside batch silo at the *doghouse* whose design depends on furnace type. The batch is heated up to typically 1500 °C at the *melting end* on one side of the tank, which can include a dam wall as well as bubbling and electrical-boosting systems to achieve complete melting. Sometimes in a *refining bank* that is shallower and hotter than the other parts of the melter, the distinct steps of primary and secondary fining then follow to yield a chemically homogeneous melt bearing as few defects as possible at the *working end* on the opposite side of the tank (Chapter 1.3). There, the melt is delivered through the *waist* (or *neck*) for float glass (Chapter 1.4), the *throat* for container glass (Chapter 1.5), or by overflow for rock wool (Chapter 9.13). Depending on the kind of furnace used, the melt is then *conditioned* on its way to the forming devices so as to reach the appropriate homogeneous temperatures and viscosities required by the process. To achieve the temperature reduction of 150°C for example needed for container production, the glass is cooled at the center of the feeder canal but need to be heated at the sides where cooling would be too fast.

The volume of the space left above the tank up to the *crown* depends on the heating system, being small for electric melting but large to accommodate the burners of a combustion chamber. Whenever flue gases are produced, furnaces include either *regenerators* or *recuperators*, which are of the same types as those used in other high-temperature processes [3]. As originally designed in the nineteenth century, regenerators transfer discontinuously heat that would be lost to the chimney to the combustion gases before they reach the burners (Chapter 10.9). They consist of two or of an even number of chambers designed to store as much heat as possible in a checkwork of refractory bricks (a *checker*, for short). In one chamber, the flue gas typically cools from 1450 to 600–400 °C while the combustion air may heat up to a maximum temperature of typically 1100–1300 °C in the other chamber; the additional heat thus delivered to the combustion space increases the heat set free in the furnace beyond the level reached by the net calorific value of the fuel alone (Chapter 9.8). Every 20–30 minutes, depending on the *thermal load* of the furnace, the flows of both fluids alternate in less than one minute during which firing stops. With recuperators, heat is in contrast exchanged continuously between the flue gas and combustion air through a co- or counter-current. What then matters is not the capacity of the exchange medium to store heat but to transport it rapidly. These devices are often termed *radiative* recuperators because of the nature of heat transfer from the hot flue gas; the colder combustion air is in contrast heated up by convection only, up to 750 °C with the most efficient systems. Thin-walled materials are required for the exchange. For mechanical reasons, high-temperature steels must be selected but they severely limit the entry temperatures of the flue gas. Although recuperators are theoretically more efficient than regenerators, they do not reach the efficiencies of regenerators in glass furnaces.

Sometimes with the help of electrical boosters, the batch is most frequently melted by the heat radiated directly by the flames (adiabatic temperatures of about 2700 and 3000 °C for air-fuel and oxy-fuel combustion, respectively; technical temperatures of 1650–1800 °C for both cases) and indirectly by the crown at typically 1600 °C (Chapter 9.8). Since the 1960s, burners are fueled with natural gas (methane, CH_4) or preheated heavy oil atomized in a nozzle by means of pressure or compressed air or methane. Solid fuels are mainly used in China where petcoke, a residue from petrochemistry, is transported to burners by means of propellant air.

2.2 End-Fired Regenerative Furnaces

Because they are economically efficient for various kinds of production (Table 1), end-fired furnaces are at present the most common. They have two ports equipped with 2–4 burners each and located on a single side next to the regenerator (Figure 1a). The flames from one port develop over the whole length of the furnace and turn 180° back toward the other port where the flue gas is extracted. This U shape gives them a long residence time. Their advantages are a highly preheated combustion air and a relatively low energy consumption. As a result, they have a high thermal and overall energy utilization efficiency, which translates into a high production efficiency and a high specific load. Owing to this efficiency, they are becoming extensively used to produce container glass. As a disadvantage, they allow for a limited control of energy distribution along the longitudinal axis of the furnace, which results in some limitations to achieve an ultimately high glass quality. Their investments costs are relatively high, however, as are their NO_x emissions, and they require maintenance work for chamber cleaning and fixing expansion joint areas for furnaces larger than 10 m.

2.3 Cross-Fired Regenerative Furnaces

By far the biggest ones, cross-fired furnaces are mostly dedicated to float glass (Table 1). From 4 to 8 burner ports are placed on two opposite sides next to the regenerators (Figure 1b), so that the temperature profiles along the longitudinal axis of the furnace can be tuned to obtain for primary fining a hot spot of a given size at the right place. This results in an enhanced control of glass quality, an important issue since the presence of a single tiny seed may lead to the rejection of a large flat glass sheet. Cross-fired regenerative furnaces are less energy efficient and reach lower specific loads than end-fired furnaces. The arrangement of the regenerators makes them more

expensive to build. And a latent problem in float furnaces is the clogging of the first chamber sections of their regenerators by the dust carried by the flue gas.

2.4 Recuperative Furnaces

Float glass is the main product not melted in the other kinds of furnaces (Table 2). In *recuperative* furnaces (Figure 2a), firing has the advantage to be continuous. From 5 to 15 burners are placed on both sides so that temperature profiles can be tuned finely. Other advantages are low NO_x emissions for container glass, a clean combustion air, and low investment costs due to relatively low air preheating, with the resulting disadvantage of high energy consumption and, thus, of lower furnace efficiency.

2.5 Oxyfuel Furnaces

Dating from the 1990s, oxyfuel furnaces (Figure 2b) are recent developments. The oxygen content of the combustion gas is increased to 91–98 vol % to avoid the energy wasted for heating the 78% nitrogen (and 1% argon) of the air up to the combustion temperature and reducing at the same time NO_x emissions and the volume of flue gas produced. The oxygen is generated on site either cryogenically or via pressure swing absorption by zeolite molecular sieves or, alternatively, is delivered as a liquid in tanks or by a pipeline from the production site. The efficiency is much higher for oxyfuel than for other fired furnaces so that the specific load is also higher. A very good adjustment of the temperature profile over the furnace axis is again possible, but condensates are generated by the wet waste gases. Oxygen generation not only means very high operating costs, however, but often difficulties for suppliers to backup the availability of liquid oxygen beyond a certain tonnage. In Europe and most parts of the world, oxyfuel furnaces are profitable only if electricity costs are less than

Table 1 End- and cross-fired regenerative furnaces.

Glass type	Size (m²)	Yield (t/d)	$NO_x{}^a$ (mg/Nm³)	Size (m²)	Yield (t/d)	$NO_x{}^a$ (mg/Nm³)
	End-fired			*Cross-fired*[b]		
Tableware	10–160	20–300	950–1500	25–150	30–280	
Borosilicate	15–50	15–60		20–60	20–60	
Ornamental	20–130	50–260		30–120	50–260	
Container	25–225	50–800	550–750[c]	30–210	50–750	
Float	250–450	375–600		205–850	250–1100	1200–1500[c]

[a] 1 Nm³ (normal cubic meter) = amount of gas in a volume of 1 m³ at 273 K and 1 atm; values relating to 8% remaining oxygen and dry flue gas, which depend on the type of refining system.
[b] For 2-burner systems; 700–1000 mg/Nm³ for 3; and up to 2000 mg/Nm³ for special glasses.
[c] 550–750 mg/Nm³ with heavy oil, 700–1000 mg/Nm³ with natural gas.
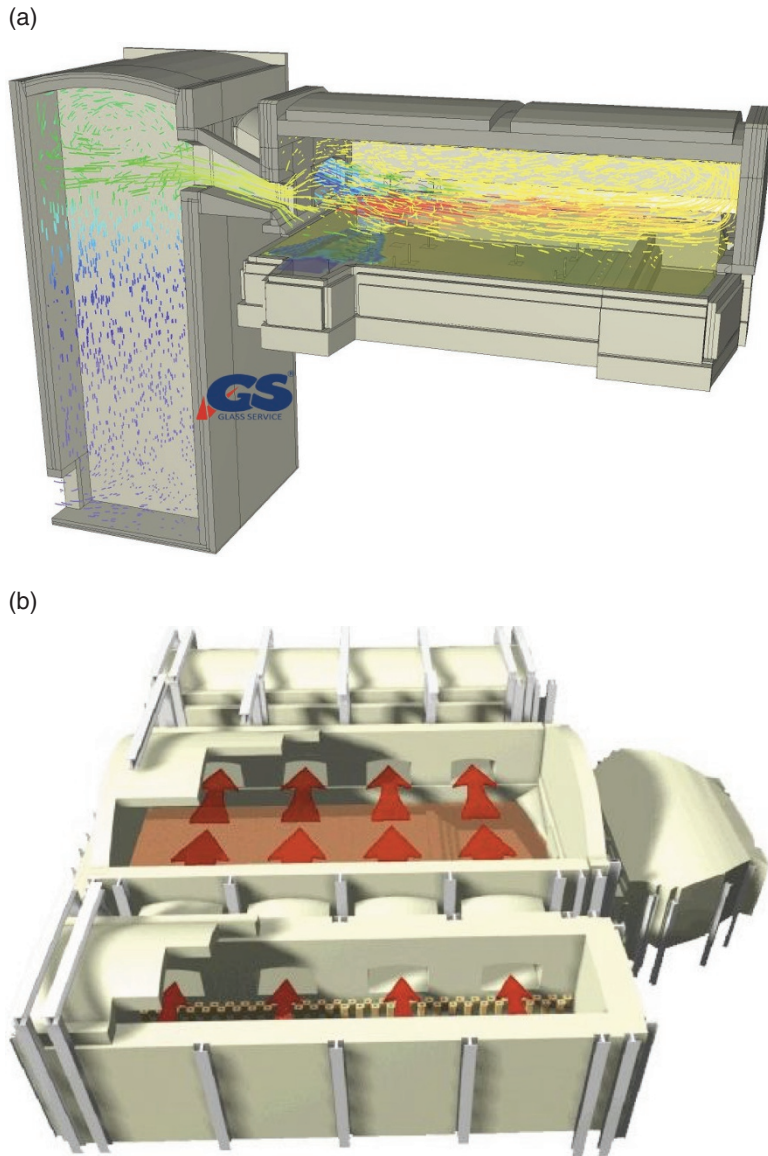
(a)

Figure 1 Regenerative fired furnaces for container glass. (a) End-fired, standing against its regenerator; hot flue gas of the U-shaped flame penetrating in one chamber to be cooled downward, combustion air coming up from the other chamber. *Source:* Sketch courtesy Glass Service. (b) Cross-fired, in between its two long regenerators. *Source:* Sketch courtesy Horn Industries AG.

(b)

Table 2 Summary of other furnaces.

Glass type	Size (m^2)	Yield (t/d)	Size (m^2)	Yield (t/d)	Size (m^2)	Yield (t/d)
	Recuperative		*All oxyfuel*		*All electric*[a]	
Tableware	15–80	20–140	15–100	40–240	3–30	6–100
Ornamental	30–130	40–260	60–100	80–250	15–30	30–70[a]
Container	30–175	50–500	70–160	150–600	30–90	0–200
Special	15–50	15–60	4–50	6–60	1–5	
Other	3–15	5–15[b]	35–100	50–250[c]	30–50	50–150[d]

[a] Opale glass.
[b] Lead-crystal glass.
[c] Fiber glass.
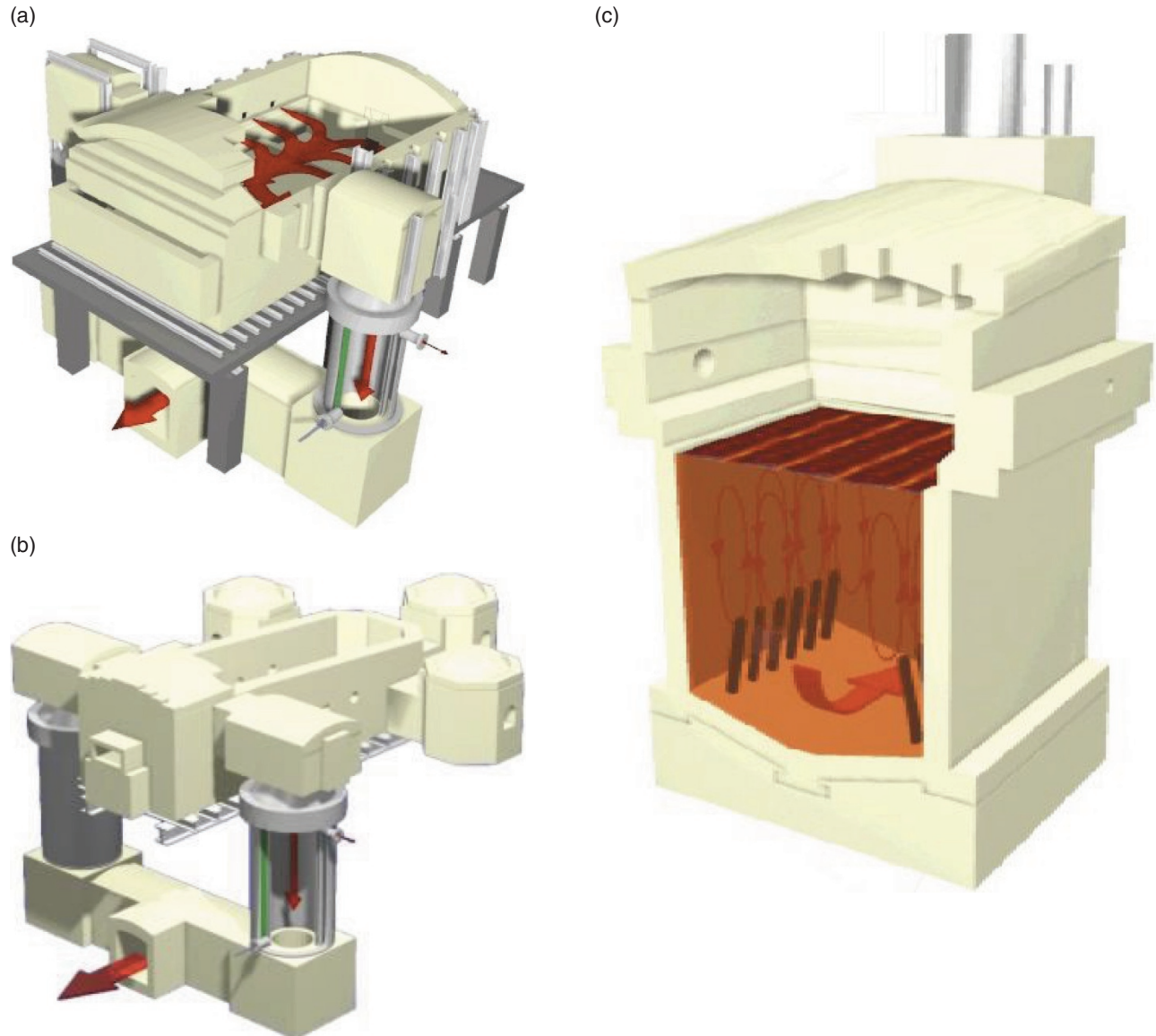[d] C and E glass (Chapter 1.6).

(a)

(b)

(c)

Figure 2 Specimens of other types of furnaces. (a) Recuperative furnace for container glass, with its tall vertical recuperator; (b) recuperative furnace for lead crystal glass; (c) all-electric-melter for tableware glass. *Source:* Sketches courtesy Horn Industries AG.

0.035 €/kWh (2018 value). They are nonetheless drawing more interest for environmental reasons especially in the United States. An interesting development has been brought to the market by Praxair Co. with the OPTI-MELT™ system, which uses a regenerator for preheating a mixture of flue and natural gases to produce a synthetic gas that is then fired with oxygen. By this process, part of the thermal energy of the waste gas is converted into chemical energy to enhance efficiency.

Oxyfuel furnaces are by definition especially advantageous if higher melting temperatures are required (e.g. for cover glass above 1700 °C) and for the production of glass of a very high quality. Cases in point are continuous fibers for which even microscale defects (i.e. inclusions or local composition variations) cause breakage of the thread in the drawing machine. To ensure excellent quality, however, boosting and/or bubbling systems as well as different wall types and even a refining bank can be needed. When float glass is made with two production lines, an all-oxyfuel furnace also makes sense because the waste nitrogen is recycled in the atmosphere of the two tin baths (Chapter 1.4) while energy consumption with 100% oxygen may be reduced by 25 % and emissions of CO_2, SO_2, and NO_x by 15, 38, and 83 %, respectively.

2.6 All-Electric Furnaces

As indicated by their names, all-electric furnaces (Figure 2c) melt the batch with intense electric currents delivered by arrays of electrodes immersed in the molten glass [5–7]. Earlier, electrodes were made of graphite but they suffered from short operation times of 1–5 months and current densities of 0.3 A/cm^2 only. Today, currents of typically 200 V and 4000 A per array are most frequently delivered by electrodes made of molybdenum, which stands out by its high melting point of about 2600 °C and its high thermal-shock resistance ensured by a low thermal expansion but gets highly corroded under strongly oxidizing conditions. Molybdenum is available in diameters from 30 to 150 mm and lengths up to 2.5 m. The electrodes are operated at voltages of 200 V, 50 Hz AC, and reach current densities of about 1.5 A/cm^2 corresponding to currents of 1–3 kA per electrode array.

For high-purity optical glasses, Pt or Pt-Rh electrodes are used at current densities of up to 2 A/cm^2. They have excellent corrosion stability in oxidizing melts but are sensitive to reducing conditions and must be operated at AC frequencies of typically 1–10 kHz below which metal dispersion into the melt would take place. Other electrode materials like SnO_2 (0.5–0.7 A/cm^2), W, or $MoZr_2$ are used in special cases only.

Electrodes are also widely used for additional energy input in fossil fuel-fired furnaces. This is obviously advantageous in terms of NO_x emissions. For container glass, however, fully electric melting of colored glass is not possible when strong ion absorption in the infrared (Chapter 6.1) makes heat transfer inefficient within the bath. Very expensive backup systems for uninterruptible power supply are in addition needed and the efficiency loss caused by high-voltage lines from the power station is often not considered, which is to be viewed critically from an environmental standpoint.

3 Melter

3.1 Alumina–Zirconia–Silica Refractories

The lifetime of a furnace is determined by the wear of its refractories. A major advance in furnace design thus resulted from the invention of electrofused cast alumina–silica materials in the 1920s (Chapter 10.9), which are highly refractory and have a porosity as low as 1–2% to reduce the interface reaction with the melt to a maximum extent. In addition, the material must have good mechanical properties at the working temperatures and be in particular resistant to thermal shock. Nowadays these constraints are best satisfied with electrofused alumina–zirconia–silica (AZS) where the ZrO_2 component ensures a unique combination of strength, fracture toughness, high ionic conductivity, and low thermal conductivity [8]. In glass melting, zirconia is also important because of its low reactivity with silicates and the high temperature of 1800 °C of the eutectic of the system Al_2O_3–ZrO_2–SiO_2. Commercial compositions are typically close to that of this eutectic with about 40 wt % Al_2O_3, 40 % ZrO_2, and 20 % SiO_2.

It was initially thought that lower ZrO_2 contents would be preferable because of the stresses induced by the volume changes of the monoclinic–tetragonal phase transition of ZrO_2 at 1000–1200 °C on heating and 1000–800 °C on cooling [8]. The opposite has found to be true, however, because the microstructure of these refractories is the key to their properties. Upon cooling of the electrofused melt, baddeleyite (ZrO_2) usually forms first but eutectic precipitation rapidly takes place in the form of closely entangled skeletal zirconia and corundum (Al_2O_3) laths. These find themselves embedded in 10–20 vol % of a Zr-bearing aluminosilicate glass [1, 9], which is soft enough at the temperatures of the zirconia phase transition to accommodate the stresses it produces. The baddeleyite crystals have a morphology that makes it difficult to expel them from the material upon corrosion and, on the contrary, help to keep the corrosion products in place. Upon fabrication, elements like sodium are added as fluxes whereas oxygen is bubbled through the AZS melt to oxidize any carbon from the electrodes and other species that could react with the molten glass.

The corrosion rate of ASZ does depend on composition, however, being much faster for calcium aluminosilicates than for soda-lime silicates [10]. In the latter case, corrosion begins by sodium diffusion into the amorphous phase of the refractory [9], first causing corundum dissolution and, in contrast, baddeleyite growth due to Zr oversaturation of the newly alkali-enriched phase [11]. At the same time that the microstructure of the refractory keeps degraded in the bulk by other phase changes, the sodium aluminosilicate phase exudes at the surface, leaving cavities at the waterline of the tank that are enlarged by the mechanical wear of the moving molten batch [12]. The corrosion rates are lower for larger checker volumes and they also depend on the sizes of the furnace and melting area, cullet fraction, specific load, boosting, and numbers of job changes. The yearly wear rate typically ranges from 1 to 3 %, but examples of 120 m^2 furnaces associated with large regenerators of 3.3 m^3/m^2 show that rates as low as about 0.4 % during the first three years of operation can be achieved for 5 % boosting and a cullet fraction of about 20 %. The rates of 0.8–1.1 % observed during the following eight years confirmed that slightly higher investment costs do pay off.

For melting C and E glass (Chapter 1.6), basalt (Chapter 9.3), and other special glasses, Cr-based refractories are alternatively used. With a melting point of 2435 °C, Cr_2O_3 is significantly more resistant to corrosion in silicate glasses than AZS but is much more expensive. Whereas AZS costs from 4000 €/t for bottoms and 8000 €/t for walls and throats, respectively, the price of isostatically pressed chromium oxide is 30,000 and 40,000 €/t for palisades and troats, respectively.

3.2 Tank

The melter is divided into the tank in contact with the glass and the superstructure. In the former, the depth of the glass generally ranges from 900 to 1400 mm (Table 3). The melting and refining ends may be separated by a single- or double-row *dam* or *weir wall* to let the colder glass rise from the bottom for being heated and fined (Figure 3). By enhancing convection and avoiding shortcuts in the flow, one increases output, ensures the required quality, or improves production flexibility and energy consumption. Such a dam can be made of 41% ZrO_2 AZS or of a dense Cr-based refractory and

Table 3 Bath depths: typical ranges and [in brackets] extreme values (mm).[a]

Tableware	900–1300 [1400]
Container glass[a]	
Standard green	900–1400 [1700]
Flint	1100–1600 [1700]
Amber	1000–1500 [1600]
Special	750–1000 [1200]
Float	1100–1500

[a] Depths of up to 2800 mm in the refining end.

may need to firmly "anchored" in the furnace bottom by a specially shaped block.

The bottom of the tank consists of refractory layers whose number, nature, and thicknesses are determined by the operating conditions. It typically consists of five layers with different functions.

The first upper two layers make up the *paving*. These are plates of fuse-cast ASZ or, for very corrosive melts without specific requirement for glass color, Al_2O_3–Cr_2O_3 plates of about 120 mm thickness paved in offset stacking (i.e. such that the joints of the lower layer are covered by the upper plates). It is of utmost importance that no bubbles are generated at the brick-melt interface. Below the paving, a layer of zircon ramming mass, about 80 mm thick, absorbs the tensions caused by the thermal expansion of the paving during heating-up. It also effectively stops any metal drops and small amounts of glass melt that locally penetrate the paving. The mechanical support is secured by the forth layer (200 mm) made of material from the sillimanite (Al_2SiO_5) family. This layer has to carry the load of the glass melt and the upper refractory layers, which amount to 3.5–4.5 t/m² depending on the depth of the glass bath or even 8 t/m² for a deep fining zone. It is directly connected to the steel framework supporting the entire construction. The fifth layer is made of light chamotte bricks. Its function is the thermal insulation of the bottom; its thickness is chosen according to the desired function.

Because the refining end can be as deep as 2800 mm for color container-glass furnaces, its design must prevent the melting part from pushing toward the throat whereas bottom electrodes may be installed next to and also often in front of the throat. The bottom refractories of the refining end are usually the same as those of the melting part, but some layers can be omitted to comply with building requirements or to increase heat losses for glass preconditioning. The entire melting and refining parts are edged by a basin consisting of a combination of 200–300 mm
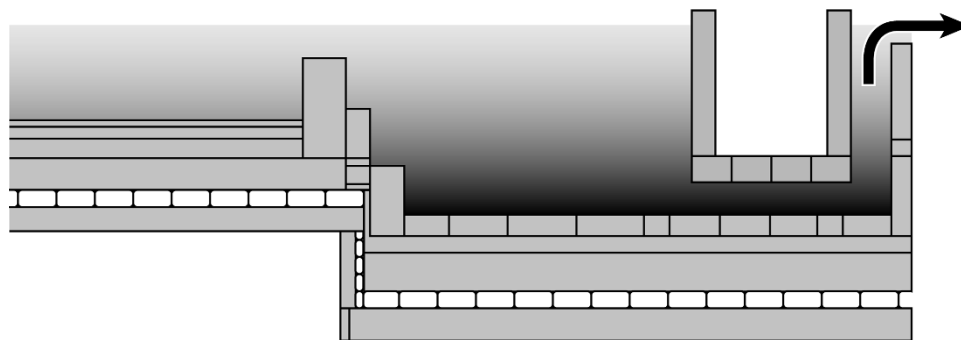

Figure 3 Sketch of a dam wall in the melter of a glass furnace.

thick soldier blocks, arranged without any mortar, between which empty spaces of about 2 mm must be left to let the blocks become tightly packed at 1550 °C through thermal expansion. To account for thermal expansion mismatch between layers, a special arrangement of steel bracing allow all bottoms layers, the wall and the palisades to be loosened upon heating up while ensuring that no joints remain open.

3.3 Additional Tools: Bubblers and Boosters

For colored glass, a dam can lead in front of the wall to *dead* areas without flow so that the effective bath volume is reduced. For sustaining flow in the entire volume of the melting end, a first means is to blow from the bottom large bubbles of air, oxygen, or nitrogen at a certain distance before the dam wall through a specific number of nozzles made of $MoSi_2$ or ceramics (sometimes sheathed with a Pt alloy), which may be water-cooled to be protected from corrosion. One then increases the specific load of the furnace by causing colder melt present at the bottom to rise toward the surface through local convection currents created around the paths of the bubbles, but at the price of an increased energy consumption.

Depending on color and cullet fraction, bottom electrode blocks are in addition often displayed according to well-defined patterns in numbers that depend on furnace size and required output. The initial bottom and the soldier blocks of the melting end can be specially shaped to enable the installation of such bubbling or boosting systems at a later stage. Boosting can be permanent or required only for certain tonnages in ways that depend on bath depth and electrode arrangement. It has obviously an important impact on the energy efficiency of the furnace. The maximum specific electrical energy to be applied to avoid premature corrosion in a bottom-boosting system is known empirically. For container glass, intensities of 1.5 A/cm^2 are briefly exceeded in some cases whereas the maximum is 0.8 A/cm^2 with molybdenum electrodes for other glass types. Depending on size, there may be several electrical circuits. Some 175 m^2 end-fired furnaces designed for the Indian market have, for example, an installed boosting capacity of about 6 MW, divided into four different circuits.

3.4 Superstructure

The superstructure of the melting furnace consists of walls (port gable, breast, and throat) capped with the crown. The walls have peep holes for inspection of the melting end (Figure 4) and openings to measure the furnace pressure as well as the temperature of the inner crown with lateral optical thermocouples. Likewise, the
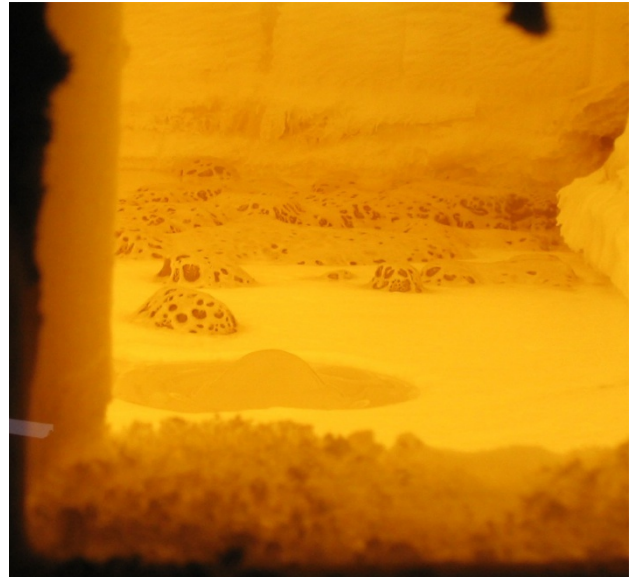

Figure 4 A view over a wool-glass bath through the peep hole of the melter. *Source:* Photo Isover Saint-Gobain, courtesy Jean-Luc Bernard.

flame and the batch distribution are inspected with a camera – or two, for the large float furnaces – installed in the throat gable, which could be combined with an infrared unit for additional temperature measurements.

Nowadays, the superstructure is mechanically independent of the glass-contact section, thanks to the *tuckstone* on which its walls rest, whose weight is exerted on the steel bracing support. A 40 mm joint filled with fiber wool separates the tuckstone nose from the soldier blocks, which can thus freely expand upon heating before being shut closed manually from the outside by a ramming mass or metal oxide–metal welding. Fused-cast AZS bricks backed up by high-alumina refractory layers of the required thicknesses are used to obtain an appropriate temperature profile within the walls. For parts in contact with flames, ceramic-bonded AZS bricks make it possible to use 2 × 1 m ZEBRA™ blocks and to prevent the so-called glassy phase from being exuded and causing glass defects.

As for the crown, it is either freely suspended or rests directly on the side walls with which joints have to be sealed after heating but before tank filling. Depending on the total length, it is split into segments about 4000 mm long. It is made of mullite ($3Al_2O_3 \cdot 2SiO_2$) layers, or of AZS for certain glass types, which is most generally lined with silica, especially of a "lime-free" kind to sustain temperatures as high as about 1640 °C. Thermocouples are installed either directly or indirectly. It is because they always represent a weak point over the service life that the aforementioned optical means are paid much interest.

3.5 Operating Features

3.5.1 Batch Loading

As far as possible any contact between the various refractories of the melter and the reactive batch should be avoided to prevent premature damage. For float glass furnaces, pusher-type planar chargers are used to supply the batch as a carpet onto the bath. For container glass, batch piles are often pushed into the furnace by tappets that can forward the batch either horizontally or at different angles. But the most common type of chargers is a chute whose vibration intensity determines how much batch and cullet are supplied. Water-cooled paddles are often installed as an oscillating system in front of such vibrating chutes, which plunge into the glass bath and thus divide the batch into piles that melt much more easily. If the upper part of the charger can be pivoted, then the batch can be directed toward the furnace, which is essential not only for end-fired furnaces having a single doghouse, but also for elongated furnaces (length-width ratio >1.75) with a load higher than 3.3 t/d.m^2. If the batch piles cannot be divided in distinct parts, *crocodiles* form as snake-like batch piles that melt very slowly and mostly settle on the opposite furnace side, causing high corrosion in the flux line area. Such an irregular settling of the batch translates into unstable temperatures in the superstructure and can influence NO_x values. Screw chargers are also used, but for special glasses for which they "only" deposit the batch onto the surface. An advantage is to allow for tight sealing of the doghouse, but batch materials must not abrade the screw to avoid defects and discoloration especially in low-iron and special glasses.

3.5.2 Monitoring

Measuring and control technologies are of vital importance for running furnaces. The furnace pressure must be monitored near the glass bath to limit (i) any flame influence, which could cause spurious signal perturbations, and then improper pressure regulation; (ii) glass-level fluctuations and in the end production losses due to weight fluctuations of the gob especially with high-output IS machines for lightweight container glass (Chapter 1.5). The glass level in the tank and partial pressures of O_2, CO, etc., are also monitored.

Temperatures must also be continuously measured with thermocouples in the regenerator section, furnace superstructure, and glass contact zone for ensuring production stability in every respect. Two different process-control systems are in fact used. The most straightforward would be to regulate the fuel consumption to make sure that the temperature measured at a given place remains equal to the set point appropriate to the batch composition. Because thermocouples age with time, however, the refractories could be massively damaged and the crown totally damaged if a spurious temperature drift were not detected. In the second process, therefore, one rather checks the fuel consumption and considers the temperatures measured in the superstructure only as indicators. In both cases, however, it is very helpful to make detailed pyrometric measurements to detect possible thermocouple aging and to use reliable "EXPERT" systems to compile and analyze continuously all measurements to identify any problem and fix it immediately for stabilizing the production process.

4 Heat Management

4.1 Burners

The design and arrangement of burners are really important issues. To control both flame size and shape, burners are equipped with an inner and an outer nozzle fed
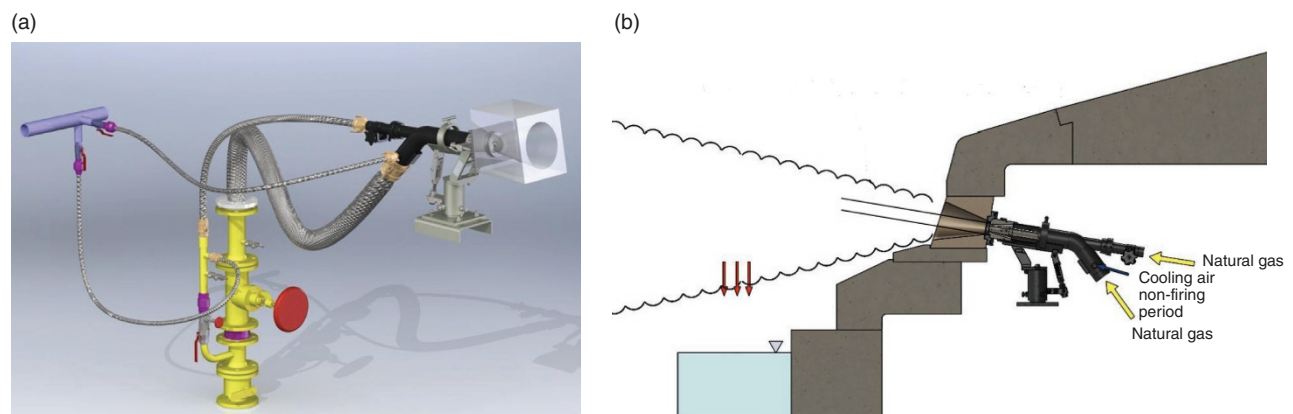
Natural gas

Cooling air non-firing period

Natural gas

Figure 5 The two nozzle of gas burners (a) and the resulting gas flow (b). *Source:* Courtesy FlammaTec

by main and secondary fuel gas streams, respectively (Figure 5). In a simple design, the incoming gas stream is divided manually by means of a valve directly attached to the burner. With a more advanced, but expensive method of fuel regulation, the relative positions of both nozzles can be varied, too, to produce very specific flame geometries for primary NOx control. To stabilize the flames or reduce pollutant emissions, other tools can be installed in the superstructures of the melter. These include oxy-enrichment of the combustion air by pure oxygen, combustion with staged burners, and systems such as ggENOx™, which oppose the flow of flue gas to increase its recirculation and, thus, its residence time.

4.2 Regenerators

The refractories of the regenerators are a driver of the overall investment costs because they represent about 70 % of the total mass of a furnace. As illustrated by an end-fired regenerative furnace (Figure 6), so many parts should be considered for a detailed description of a regenerator that only a few essential elements will be mentioned here. Most important in this respect is the *port neck*, which connects the regenerator to the melter. On the one hand, the differential expansion, especially vertically, of the regenerator and melting end must be adjusted so as to avoid any unintentional shift and keep the expansion joints in the entire sections
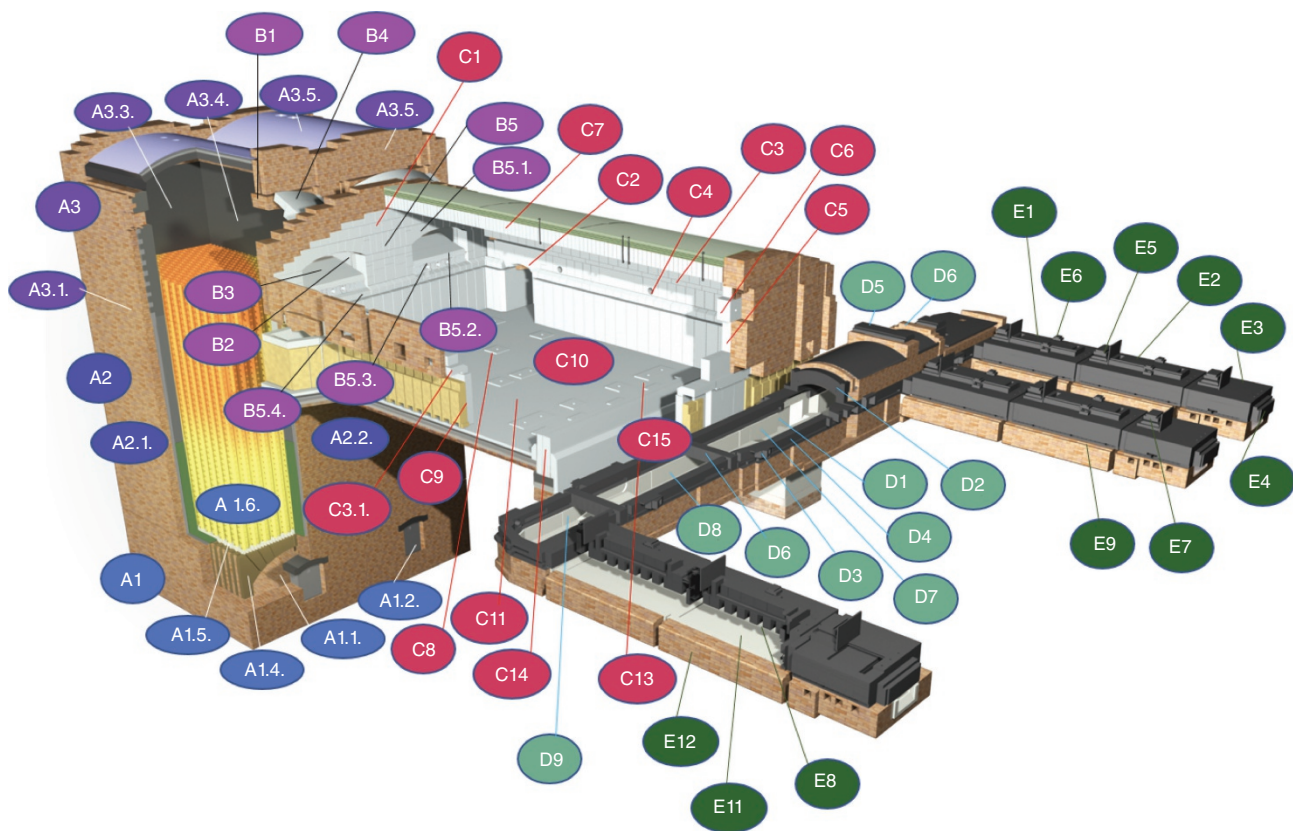

Figure 6 Individual components of an end-fired regenerative furnace.
A. *Regenerator*: 1. Downpart: 1.1. bottom, 1.2. wall with cleaning openings, 1.3. flue gas channel (not visible here), 1.4 rider arch, 1.5. spanner tiles and transition layer, 1.6. checker work; 2. Central section: 2.1. side walls, 2.2. front wall (opposite side: rear wall; orange interior: checker work); 3. Head: 3.1. side walls, 3.2. entrance wall, 3.3. target wall, 3.4. middle wall, 3.5. crown.
B. *Port neck*: 1. regenerator entrance arch, 2. side wall, 3. bottom, 4. cap or crown, 5. port mouth: 5.1. entrance arch blocks, 5.2. apron block, 5.3. burner blocks with distance blocks in-between, 5.4. tuckstone block;
C. *Melter*: 1. back wall above port mouth (port gable wall), 2. doghouse entrance arch, 3. breast wall with backup layers and insulation, 3.1. tuck stone, 4. peep hole, 5. front wall or throat gable wall, 6. TV camera block, 7. crown, 8. doghouse with cover, 9. basin with soldier blocks and insulation, 10. melting end, 11. tank bottom, 13. bottom electrodes, melting end, and barrier boosting, 14. weir or dam wall, 15. refining end, 16. throat, 17. riser with distributor entrance;
D. *Distributor*: 1. entrance zone, 2. center forced cooling devices, 3. peep hole, 4. pencil burner lining, 5. radiation opening, 6. zone dividing wall, 7. basin and bottom, 8. heating/cooling zone, 9. alcove as heating zone.
E. *Feeder*: different components not explained in detail.

perfectly closed. On the other hand, the port neck must ensure an optimum energy supply to the glass bath and also, in combination with burner arrangements, low NO$_x$ values, while preventing critical corrosion of the breastwall and/or crown in the melting end. On the furnace side, these functions are exerted by the *port mouth*. Its bottom is generally lined with AZS and its other parts also of AZS material for glass containers or of other materials such as mullite or magnesia (actually made up of 80% MgO along with Mg aluminates, silicates, ferrites, etc.), which are outwardly insulated with differently graded materials.

On the regenerator side, the entrance bears the highest load because of the contrasting temperature conditions of the firing and flue gas phases and of chemical attack from fuel and batch vaporization. The regenerator head with its special volume ensures that the flue gas is well distributed into the checkers to store in 20–30 minutes a maximum of heat to be then transmitted to the combustion air. The same applies to cross-fired furnaces, with the difference that the flue gas leaves the superstructure on the opposite side and then preheats the opposite regenerator side. This arrangement does not apply to recuperative furnaces and oxyfuel furnaces with continuous and permanent firing from either side.

In the overall stability of the regenerator walls, expansion in both horizontal vertical directions is considered. The lower part of the regenerator, the *downport*, has openings for cleaning. Its *rider arches* and then *spanner tiles* and transition layers are mainly made of fireclay bricks; sillimanite, high-quality sillimanite, or even mullite or silica then become employed when the flue-gas and combustion-air profiles reach a temperature of about 800 °C. The checker rests on this basis. Its elements have been designed in various ways to optimize gas flow. The most common are the chimney-block and cruciform checkers, whereas straight basket-weave and staggered grid packing are also alternatively used outside Europe. Not only are higher-quality refractories successively implemented but they also must be compatible with the fuel used and the batch composition, but their thickness increases up to the regenerator head whose target wall is disproportionately stressed in comparison with the port neck.

The reversing unit separates the combustion-air from the flue-gas flow. Combustion air is sucked up via a fan and blown in via the air-connecting box of the reversing unit to pass through the downpart regenerator, to be preheated in the checkers, and eventually to reach the regenerator head from where it enters the melting end through the port neck. As for the fuel, it is brought through the port neck bottom by a special lance, located laterally in the port mouth or beneath the port-apron block, to the burner blocks where the flames form and are shaped.

Since the entire system is hydraulically connected, it is of vital importance for end-fired and cross-fired furnaces that the reversing process be smooth and gentle not to cause level fluctuations at the melting end, which would propagate downstream. In end- and cross-fired furnaces, one can reduce the impact on the glass level by igniting burners and burner ports at staggered intervals. In end-fired furnaces, the U-shaped flame is deflected at the throat gable wall and then passes through the other port neck.

4.3 Recuperators

Ceramic systems are often operated with a *falling* flue-gas flow. When they are brand new, heat from the flue gas exchanged in cross flow via shaped ceramic bricks brings combustion air to 1000–1150 °C, a range that almost reaches that of regenerators. When the system ages, however, complete separation between the air and flue-gas flows is no longer achieved so that preheating temperatures decrease and more air must be supplied to ensure the stoichiometry of the combustion reaction. In addition, dust deposits from the batch in the upper layers corrode their ceramic bricks and minimize heat exchange. Brief interruptions of the combustion-air flow due to power failures also affect the tightness of the systems because of overheats in some parts of the recuperator and then of the formation of cracks and joints upon gentle restart after shutdown.

Metal recuperators thus tend to be preferred because of the intrinsic fragility of ceramic systems. They can be designed with rising as well as with falling flue-gas flow. The former design is frequently chosen when condensates and re-sublimates form since gravitation bring the solid particles back into the hot section from where they can be removed, when almost liquid, via special openings in the recuperator bottom. This design is also often used when a lack of emission requirements allows the flue gas to be discharged freely. In this case, the control of the furnace-pressure dampening and the chimney installed behind the recuperator are used permanently, and not solely in case of emergency as with other systems. Falling flue-gas is in contrast frequent to integrate an existing channel that leads through a filter to the chimney. The disadvantage is that condensates and re-sublimates forming upon cooling of the flue gas can accumulate or deposit on recuperator parts, reducing heat exchange, lowering the preheating temperature, and eventually causing slow plugs up and furnace problems.

Metal recuperators are basically of two kinds, which can be combined in different ways to increase preheating temperatures from 650 to 750 or even 800 °C, the highest working temperatures of current alloys. Higher temperatures could in principle be reached with ceramic

compensators before the flue gas temperature has reached a range at which steel may then be used. The unsolved problem is that ceramic refractories should be thin-walled to be good heat exchangers, which is problematic for brittle materials and would result in short service lifetime.

With *double shell* or *gap* recuperators, heat exchange by radiation and convection takes place between two concentric stainless-steel shells insulated with ceramic fiber and rock wool, the flue gas and combustion flowing directly or counterflowing in the inner and outer shells, respectively. To increase exchange surface, and thus heat flow, baffles or checker plates are fitted to the inner tube. These recuperators can also be used for preheating natural gas or pure oxygen up to certain temperatures. For lead glasses, preheating temperatures are generally limited to 450 °C, otherwise the recuperator would be rapidly destroyed by Pb-bearing flue gases. The *tube-bundle* recuperator whereby combustion air flows in small tubes included in the big one of flue gas is by far more expensive but can be used in higher temperature ranges without any problem. The bundle of tubes is often inserted in a part lined with refractories. Also here the tubes are corrugated to increase the surface, so a larger heat-exchanging surface for the air to be preheated is created.

Safety systems are an important aspect for all recuperators because overheating often cause distortions and cracks, which result in leaks through which the flue gas and combustion air mix. In addition, the air fan must have a permanent power supply because any interruption of the flow of the combustion air must be avoided. Another safety device is a flap opening automatically in case of power failure, through which cold air is sucked into the system to protect the inner shell. This system can be combined with a separate cooling or injector fan to achieve better cooling. Depending on the design of the entire system and on working temperatures, the combustion air could become too hot. The inlet section can thus be cooled, and the air that is not required for combustion and has already been preheated is simply "blown off."

4.4 Flue-Gas Channels

The waste gases are evacuated by channels at about 600–300 °C to the chimney after having given away most of their heat to a recuperator and/or a flue-gas purification system. To prevent concrete from overheating, cooling slots are frequently installed underneath the channel. Different grades of refractories are selected as a function of the predefined temperature of the flue gas, of possible corrosion, and also of the local economic conditions. For fast, solid, and tight construction, the side walls and the arches of the channels should be completely or at least partially cast especially for complicated and angular designs. But prefabricated parts are much helpful to reduce the erection time whereas traditional brickwork is generally chosen along with adequate thermal insulation in countries where labor cost is low.

Not surprisingly, recuperative and oxyfuel furnaces require fewer devices to be installed in the channels compared with regenerative furnaces. Only the outgoing pipes for the heat exchanger and the waste heat-recovery systems or filters are taken into consideration, sometimes along with the furnace pressure-regulation device. This happens when this pressure is not adjusted via a kind of induced draft or by means of cold injector air that expands in the hot flue gas current and, thus, creates a kind of counterpressure.

If flue gas is very wet and the potential for condensation is high, temperatures up to the filters and chimneys must be carefully checked in view of potential condensates. Within given temperature ranges, special sections and areas are inserted in the channels to reduce the flue-gas velocity so as to facilitate dropping of the particles. In oxyfuel furnaces, a widened flue-gas channel often serves as a quenching chamber to cool down the flue gas with water or cold air. A kind of "pre-cleaning" of the flue gas is then facilitated if this quenching takes place at the right speed and temperature.

In regenerators, flue-gas reversal stations must be carefully designed. Because they are close to the regenerators, they are made with gray cast-iron slides that must run smoothly on rails to keep sealing tight. If not, ingress of the so-called *false air* would be problematic as it would, for instance, adversely affect reduction of NO_x emissions. Because of temperature changes made every 20 minutes, the stresses induced enable very sturdy connections between the stations and channels to avoid any false-air ingress. In modern reversal stations, a simple mechanical safety device ensures that the flue gas is released on one side as the same time that the combustion air is introduced on the other. For big cross-fired furnaces, it may be preferable to have several smaller reversing stations instead of a big one for better handling and more targeted distribution of combustion air. This applies specially to float furnaces for which up to eight sectional regenerator chambers allow the energy input and the temperature distribution along the longitudinal furnace axis to be accurately controlled. Regenerators without internal separation walls are less expensive and easier to operate, but also less effective in the control of longitudinal energy input.

In end-fired furnaces, a new concept has prevailed since the 1990s. It was designed fortuitously – and then found more efficient – when some local configuration prevented the usual one from being implemented. It consists in letting the flue-gas channel pass beneath the melter to reach the port neck. The disadvantage of equipment

damaged in case of a glass leakage is minimized by an appropriate structure for the bottom of the melting end. As for the advantage, it is a more even and continuous flow that results in a reduced energy consumption and slower furnace aging. With units getting bigger and bigger, end-fired furnaces now benefit from a similar solution whereby three or four sub-channels are used depending on furnace size. A targeted "regulation" of the flow through the diverse parts of the regenerator is facilitated in this manner because the temperature profile in the regenerator can be controlled during the firing phase, thanks to the several ways in which the combustion air can be introduced. With such subcanals, however, ways should be carefully designed to clean the regenerator bottom from condensates and dusts.

5 Furnace Design

5.1 General Considerations

Depending on local situation, the first step consists in determining the furnace type and size and the energy to be used that would yield the best operating results as a function of the costs of energy and raw materials as they may be guessed over periods of time reaching now from 15 to 20 years. Although electrical boosting should in principle be kept as low as possible, it is more advantageous when electricity prices are lower near nuclear power stations or hydropower plants. By making the superstructure taller, one can increase the energy input in such a way that the specific load increases to a certain extent but the gain has to be balanced against higher construction and refractory costs and also higher heat losses. The issue is again considered whenever additional investments or repairs are to be made. In India, where labor and refractory costs are low compared with those of gas or oil, large regenerators are built to reduce energy consumption as much as possible. In Europe, the solution is sought more pragmatically to come close to the optimum in every respect.

Market conditions are in addition relevant for container glass. In the United States, very big Triple-Gob or Quad-Gob IS machines are often used to produce the same kind of container for more than half a year with a constant, low cullet fraction. Tanks seldom need a big wall; they are usually a little bit deeper and their specific loading capacity is a little higher but they require a well-designed working end with ample volume for good control of glass conditioning. In Europe, the available cullet fluctuates daily on the market so that its fraction incorporated varies accordingly. Melters must then be very flexible whereas Quad-gob IS machines are not common and used only for small items up to about 150 g. These melters

therefore require various tools. A wall is an important element whereas the refining end has to accommodate tonnage leaps during production. A big volume is essential to serve as a buffer storage: for a fully equipped 90 m^2 melter, an overall tonnage of 275 tpd might have leaps of about 50 tpd so that the working end must be designed as a kind of distributor channel to supply well-conditioned glass to 3–4 IS machines. For float or fiber glass, in contrast, melter design does not differ so much in Europe and America.

5.2 Empirical Guidelines

Most helpful to the furnace designer are general empirical rules that are part of the company's know-how as well as design criteria also based on experience. Not following them makes it difficult to manufacture a marketable product or to keep energy consumption, hence production costs, within reasonable limits. Although they depend on glass types, many are valid for all furnace types using fossil fuel as the main energy source. In furnace engineering parlance, an important parameter is the *load* (Chapter 9.8), which has already been mentioned and is the production rate per unit of surface area expressed in tons per day and square meter (t/d.m^2). In furnace design and construction, a modified quantity, the so-called *fossil load* plays a key role. It is defined as the fraction of the *load* sustained by the input of fossil fuel energy alone. Reaching a sufficiently high fossil load is the initial objective of furnace design; it is determined by the melting area, the length to width ratio, the height of the crown, the burner configuration, and many other construction details. The load ultimately envisaged is chiefly achieved by boosting (typically 5–30% depending on the type of glass). For this purpose, the configuration of electrodes and the dimensions of the melting space have to be designed accordingly as will be illustrated in the next section.

The more difficult it is to melt a specific glass, the more additional installations and tools need to be integrated if a high glass quality is desired. Of utmost importance in this respect is a long enough residence time in the *melting end*, including the refining part of bank, and not in the whole melter as commonly assumed. Depending on cullet fraction, glass quality, and tonnage leaps, between 18 and 20 hours are assumed to be optimal for container glass, out of average total 24 hours spent in the melter. For tableware, these figures are 26–28 and 30 hours, and they should be higher than 48 hours for special glasses.

The higher the wall, however, the more attention must be paid to avoid a stagnant area, for example, with bubbling or by boosting, which in addition stabilizes the convection current, especially in big furnaces. Boosting is in addition a good tool for modifying the temperature of the

throat inlet, the riser, and further the entrance temperature of the distributor. The higher the planned job changes in terms of tonnage differences and the more frequently these are to be put into effect, the higher an installed dam wall has to be and the deeper the refining part has to be depending on glass type.

Regarding melter geometry, the higher the specific total load of the melting end (fossil and electric proportion), the deeper the melting end must be. The narrower and smaller (<50 m^2) the melting surface, the lower the glass bath must be and the lower the specific melting output can be.

The darker the glass color, the lower the fossil melting load (flint/amber/green, some green colors can only be melted with a proportion of electric boosting or if a bubbling system is installed).

In all cases, the customer's practice is of vital importance. If side electrodes are integrated in the soldier blocks of the melting end, boosting can be used when needed with a certain basic load. But dirty bottom glass is stirred up if boosting is switched on again after a certain downtime, which first leads an increased number of seeds and inclusions. With a bottom boosting system, the bath depth must not be too low otherwise no efficient convection current can be sustained. On the other hand, maintaining the required temperatures in a deeper bath can require continuous boosting. But bottom boosting is not always compatible with a high cullet fraction because introduction of metal impurities may result in leakage and total loss of the furnace.

Although float-glass furnaces have enormous dimensions, their capacity can be compared with those of container glass. The melting part can be exposed to a specific load up to 2.5 t/d.m^2 depending on size, color, and cullet fraction. Bubblers are used for tinted glass, which are inserted to a depth of about 600 mm into the glass bath. An advantage of bubbling systems available on the market, as proposed by F.I.C. UK, is that they can be activated as a function of the color of the glass melted. Another current trend is to use more and more boosting systems with up to 2.5 MW capacity in single circuits and up to about 6 MW maximum capacity to make optimum use of the operating systems. The refining part of such a float glass furnace must also be obviously able to handle this additional capacity, the same applying to the waist and working end. Specific loads up to about 4.5 t/d.m^2 in the refining part and up to about 5 t/d.m^2 in the working end are now not uncommon.

5.3 Increasing the Specific Load: An Example with Amber Glass

The influence of the operating parameters on production costs for different overall loads per square meter of
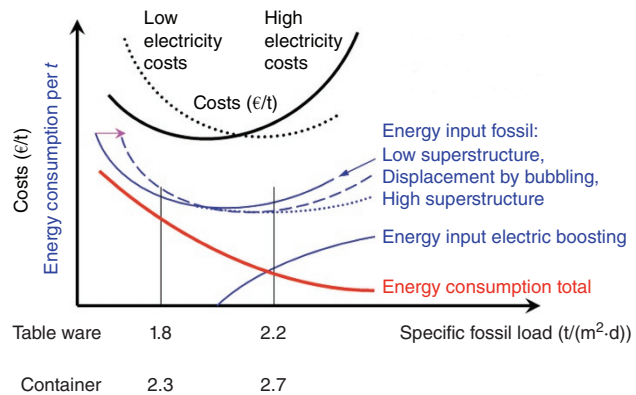

Figure 7 Energy consumption as a function of specific load (t/d.m^2) used to optimize economic furnace design for tableware and container glasses.

melting surface will be illustrated for tableware and container glass for which the energy optimum is for fossil loads ranging from 2.3 to 2.7 t/d.m^2 (Figure 7). When producing amber glass with 35% cullet, a small 45 m^2 end-fired furnace can be loaded with about 2.35 t/d.m^2 and heated with fossil fuel only to produce 105 tpd of good-quality glass having between 30 and 60 seeds/100 g, which complies with the European standard. Because it is fossil fired, the furnace cannot be very deep as bottom temperatures would be too low and glass quality insufficient. With a dam and bubblers, production could increase to 110 tpd with the same cullet fraction and glass quality, and to 135 tpd with additional boosting. For a similar furnace twice as great, i.e. of 90 m^2 size, the specific load can be 2.45 t/d.m^2 from the start, thus producing 235 tpd. This figure could be brought to 265 tpd with side boosting and to even 275 tpd in combination with bottom boosting, in which case the bath depth has to increased.

Up to 475 t/d of the same amber glass can be melted in a 180 m^2 end-fired furnace whose length of about 18 m imposes from the start an additional tool to stabilize the convection current. Although about 500 tpd can be attained with bubbling, a designer will prefer bottom boosting. Depending on the number and diameters of the electrodes, up about 2600 kWh can be supplied directly into the glass to increase capacity to 570 tpd. The overall installed boosting capacity obviously needs to be higher. With additional boosting in the melting end, preferably at the bottom for a large size, the overall tonnage can be increased from 700 to about 720 tpd provided that the bath depth has been increased accordingly.

With a 90 m^2 oxyfuel furnace, one could certainly melt up to 250 tpd of amber glass depending on oxygen purity. With regard to energy, the efficiency would at first sight certainly be the best but the energy required to produce

oxygen would of course have to be included. Also note that the figures reported for amber glass would not apply to flint glasses, for which the specific load could be higher, and for green glass, which does not melt so well and for which the iron and chromium contents have to be taken into account. Regardless of glass color, the load broadly increases in the order lead crystal, crystal, cover, and aluminosilicate glass, followed by fiber, borosilicate, and float glass, the highest loads being achieved with container glass. In general, loads can be increased by boosting, often in combination with bubbling. In summary, these amber data are only rough guidelines, which can also vary much for a given type of glass with the raw materials used and their purity. Hence, many factors must be considered to estimate which particular configuration should be most profitable for a given type of production.

6 NO_x Emissions

An NOx value of 800 mg/Nm^3 for an 8% O_2 content and a dry waste gas represents 1.2 kg of NO_x per ton for container and float glasses. This figure was regarded as a magic limit way out of reach in the 1990s. At the price of an increased energy consumption, it is nowadays the limit in front of the chimney set in Germany whereas environmental authorities aim at 500 mg/Nm^3 for new regenerative end-fired or cross-fired furnaces [5]. For oxyfuel furnaces, the limiting value is not referred to the Nm^3 flue gas, but to the amount of glass melted.

These pollutants form from nitrogen in the fuel and the raw materials, especially when nitrates are present in the batch. The formation of NO_x from atmospheric oxygen and nitrogen can take place by different routes [13]. The first identified were the so-called Zel'dovich mechanisms [14], namely a slower reaction

$$N_2 + O = NO + N \tag{1}$$

followed by the much faster

$$N + O_2 = NO + O. \tag{2}$$

But NO can also form through reactions with OH radicals or via *prompt* mechanisms [15] taking place in the flame front near the burner surface via attacks of carbon or hydrocarbon radicals on N_2 molecules such as

$$CH + N_2 = HCN + N. \tag{3}$$

The NO_x emission levels thus greatly depend on the fuel used, (excess) oxygen content, and CO content in the flue gas. Because the furnace itself also matters, other factors to be considered are its length to width ratio, superstructure height, regenerator size, and number and type of burners as emissions are lowered with fewer burners, reduced superstructure temperatures, and lower preheating temperatures of the combustion air. If more than three burners per port are used for end-fired furnaces, an increase of the NO_x values from 100 to 300 mg/Nm^3 NO_x per additional burner is to be expected, depending on the burner type and design. Similar correlations can be seen in cross-fired furnaces.

An efficient method to lower NO_x emission is to increase the CO content in the regenerator head (Table 4), but values higher than 1500 ppm may cause checker breakdown via disintegration of the refractories as a result of microcracking or even powdering. The cause is the formation of iron carbides between 400 and 600 °C from the carbon produced by the Bouduard reaction

$$2\,CO = CO_2 + C. \tag{4}$$

This reaction takes place by chemisorption of CO and its subsequent decomposition catalyzed by active Fe atoms produced by the reduction of iron oxides present in the refractories, which then participate in a second reaction to produce iron carbides [16].

Alternatively, mixing the combustion air with part of the exhaust waste gas in the downpart of the regenerator can help to lower NO_x emissions right from the reaction

Table 4 Correlation between CO and NO$_x$ contents.

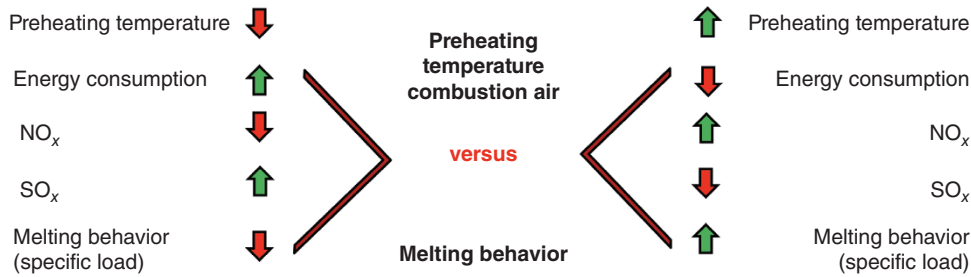| Position	CO content (ppm)		
Regenerator head	<50	<300	600–800
Regenerator downpart	None	<50	100–300
Chimney front	None	None	<100
	Corresponding NO$_x$ content (mg/Nm^3)		
Two burners installed	550–750	500–600	450–500
Three burners installed	700–900	600–800	<700

Figure 8 Interplay of factors involved in NO_x and SO_x emissions.

with the fuel at the port mouth. But the complex balance of factors to be considered also involves SO_x species (Figure 8). A lower air preheating temperature, for example, results in lower NO_x levels, but then both the energy consumption and the SO_x content in the flue gas increase and the achievable pull rate decreases, and vice-versa.

Experienced practitioners know so well these correlations that primary reduction of NO_x has almost reached its limits; potential improvements might concern only burners whose emissions could be brought down to about $300\,mg/Nm^3$ per unit. Further, NO_x decreases should thus rely on shifts of the gas-phase equilibria by selective non-catalytic reduction reactions [17]. A relevant reaction is [18]

$$NH_3 + NO + O_2 = N_2 + H_2O, \qquad (5)$$
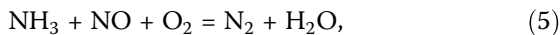
which is beneficial from 1000 down to 700 and $870\,°C$ depending on whether or not H_2 is added to the system. Temperatures higher than $1000\,°C$ should be avoided, however, because the adverse reaction

$$NH_3 + O_2 = NO + H_2O \qquad (6)$$

then predominates. Considerable reductions of the NO_x values in front of the chimney can thus be achieved through injection of ammonia or ammonia solutions into the flue gas within the right temperature window, but the investment and operating costs can amount to about 100 k€ per year depending on plant size and flue gas volume flow to be treated.

7 Perspectives

From the mid-twentieth century, a general trend in glass-making has been to develop bigger units as exemplified not only for float but also for container glass for which the IS machines keep increasing in size and production volume (Chapter 1.5). Owing to increasing industrial concentration, this trend will likely continue in the future so that small furnaces will probably remain only for producing special or highest-quality glasses. Multicolor furnaces for container glass are, for instance, designed to be highly flexible – and therefore smaller – with only one or at most two IS machines to speed up reactions in response to market situations. For usual container glass, the size of cross-fired furnaces will in contrast approach $230\,m^2$ to ensure an output of 1000 tpd. For float glass, 1000 tpd will no longer be a limit, thanks to future improvements brought to the tin bath and annealing lehr, and especially to faster operations at the cold end where the ribbon is cut and withdrawn. For lower outputs in the 600–700 tpd range, end-fired furnaces will be increasingly built in view of their enormous savings in investment costs. Once they have been implemented and the right conclusions drawn, these furnaces will certainly become larger.

Progress will also be made for the refractories. To summarize the considerable improvements already brought to their properties, it will suffice to state that in the 1930s their campaign lives and maximum temperatures were only 11–13 months and $1400\,°C$ [1]. By comparison, the service life of furnaces currently reaches about 15 and 20 years for container and float glass, respectively, during which there can be short periods of hot repair of local defects in the upper structure or, more rarely, complete shutdown and release of melt for cold repair of critically corroded areas in the lower structure. For fossil-fuel furnaces, more ceramic-bonded AZS materials will certainly be used and additional advantages will accrue if the basic idea of compound materials such as the sandwich or zebra blocks is picked up. For the superstructure, 190–250 mm blocks of pure AZS could, for example, be replaced by 75–100 mm AZS sandwich blocks, which would ensure, in combination with high-alumina refractories, the same stability and application limits. Considerable savings in investment costs could be made in this way, which would in addition limit tapping expensive zirconium resources.

In the past decade, alternative melting technologies have been thoroughly developed with the aim to increase both energy utilization and production efficiency. These
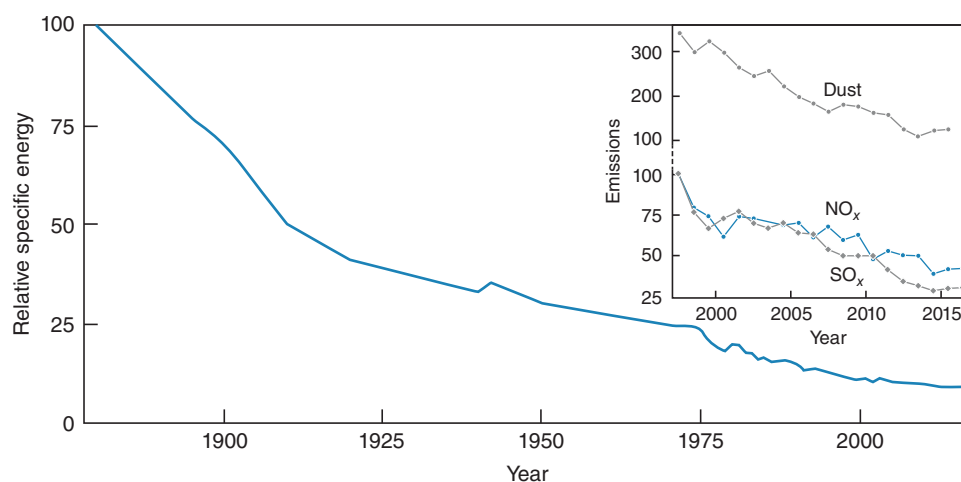
Figure 9 Evolutions of overall energy efficiency and emissions of NO_x, SO_x, and dust over the years. *Source:* Data from http://www.agc-glass.eu/en/sustainability/environmental-achievements/air

approaches comprise: (i) submerged combustion technology whereby burners deliver in a bubbler-like manner their flames from the bottom of the melting space directly into the melt; (ii) inflight technology whereby a finely ground batch is delivered directly into the flames; (iii) top vertical burners whose flames impinge on the melt surface. Even though the last one is now applied by several producers, for example, for fiber glass, none of them have fared significantly better than conventional technologies with respect to the intended goals.

From an environmental standpoint, one should finally stress the impressive nature of the improvements brought over the years (Figure 9 and insets). The evolution of the energy efficiency is especially striking with more than ten times increase since 1880, whose leveling off might suggest that the intrinsic limits of current processes are being approached. This reduction of the melting energy from 5600 kWh/t in the 1930s to 1000 kWh/t today for container glass has been largely attributable to the improvements in refractory materials. Of more recent concern are the NO_x and SO_x emissions, which a company such as AGC has been able to decrease by a factor of 4 in 20 years. A similar trend is observed for the emissions of dust, which is mainly made up of sulfates. These reductions are achieved with filters. Whenever possible the dust collected is recycled as sulfate batch components.

But enormous investments remain to be made by the glass industry at large to comply with the legal requirements worked out by the EU for NO_x emissions because many plants do not benefit yet from up-to-date technologies. New development are also being made, for example, for big all-electric melters for which, however, another challenge will be really permanent energy sources. And it will be seen whether new procedures such

as thin-melting processes or submerged-burner systems will be more successful on the market than others that have been developed in the past. As for the move toward a CO_2-free production, it would involve a still more difficult challenge as carbonates should be eliminated from the batch, which would require major changes in the raw materials used ever since the beginnings of glassmaking.

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