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Modeling, Sensors, and Furnace Design

OPTIMIZATION OF REGENERATOR DESIGN

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ABSTRACT

Improving energy efficiency and cost reduction in glass production are of key importance to maintain glass as a cost-competitive product with an environmentally sound footprint. Regenerators of glass furnaces have a major impact on energy efficiency in glass production, investment costs for new glass furnaces and maintenance costs (cleaning regenerators) during operation. The aim of improving design of regenerators is to maximize heat recovery from the hot flue gases (and to preheat combustion air) while minimizing its volume (to limit purchasing expensive regenerator bricks) and ageing. In practice, regenerator efficiency (and lifetime) depends also on the degree of clogging and fouling of the regenerator mainly caused by condensation of sodium sulfate in the regenerator condensation zone. Next to energy savings, the glass industry is further challenged to lower emissions by stricter legislation. Reducing NO_x emissions tends to direct glass companies to near-stoichiometric combustion lowering the excess of air or oxygen. However, the presence of CO at near-stoichiometric combustion increases the evaporation of volatile species in the glass furnace. Thereby, and in combination with increased CO-levels, increased clogging and fouling of regenerators are observed affecting glass furnace energy efficiency and furnace and regenerator integrity.

Optimal design of regenerators (in view of heat recovery, costs and lifetime) requires detailed 3D CFD simulations in order to determine the turbulent flows in the complete regenerator, the local temperatures of the gases and complex shaped regenerator bricks and the convective and radiative heat exchange between gases and checkers for both flue gas and air phase. This paper reports on results of detailed modeling of a single-pass regenerator. Next to 3D-temperature fields, the distribution of flue gas (and air) over cross-sectional checker layers is shown. In addition, the impact of lowNOx firing conditions (and more specifically ‘reducing conditions’) on dust loading and fouling of the regenerator chambers is discussed.

IMPACT LOWNOX FIRING ON EVAPORATION & REGENERATOR INTEGRITY

Improving glass furnace energy efficiency is one of the key targets for glass companies to keep glass production a sustainable and cost-competitive industry. One way of reducing energy consumption of regenerative glass furnaces is improving the heat recovery from flue gases by preheating combustion air. The theoretical maximum regenerator efficiency is in the order of 77%. However, practical values vary in the range of 60 – 65% [1]. As each percent (absolute) increase in regenerator efficiency results in a reduction of energy consumption with about 1.3% for container glass furnaces, significant energy savings can be accomplished by improving the flue gas heat recovery behavior of regenerators. Besides reducing energy consumption of glass furnaces, improving the flue gas heat recovery in regenerators also might lead to a more compact regenerator design with lowered investment costs.

Next to lowering energy consumption, glass companies are also forced to reduce emissions. A way to reduce NO_x emissions is near-stoichiometric combustion at which the excess of air or oxygen is lowered. A negative side-effect of near-stoichiometric combustion is the presence of CO that might result in increased evaporation of volatile components [2], like alkaline and sulfur species, from the batch blanket and hot glass melt. Increased volatilization rates of these species will increase the concentration of these components in the flue gas that can deposit in the regenerator chambers. The mechanism of condensation and the type of products formed depends on the oxidation state of the flue gas entering the regenerator.

The impact of reducing conditions (increased CO-levels and concentration of alkaline and sulfur species) on the integrity of the checker-work in regenerator chambers has been under investigation recently. To assess the chemical resistance of various types of refractory material as a function of flue gas composition (including flue gas oxidation state) and temperature, long corrosion tests have been performed with experimental systems as shown in Figure 1. A gas-air/oxygen flame (with a defined content of O_2 or CO) is established to which alkaline (sodium) and sulfur species are dosed. The flue gas is led over an array of various species of checker-work material in the temperature range similar to the condensation zone in regenerator chambers. The corrosion behavior of the checker-work is evaluated over a period of typically one week. Afterwards, the pieces of checker-work material are evaluated on corrosion products by means of SEM analysis.

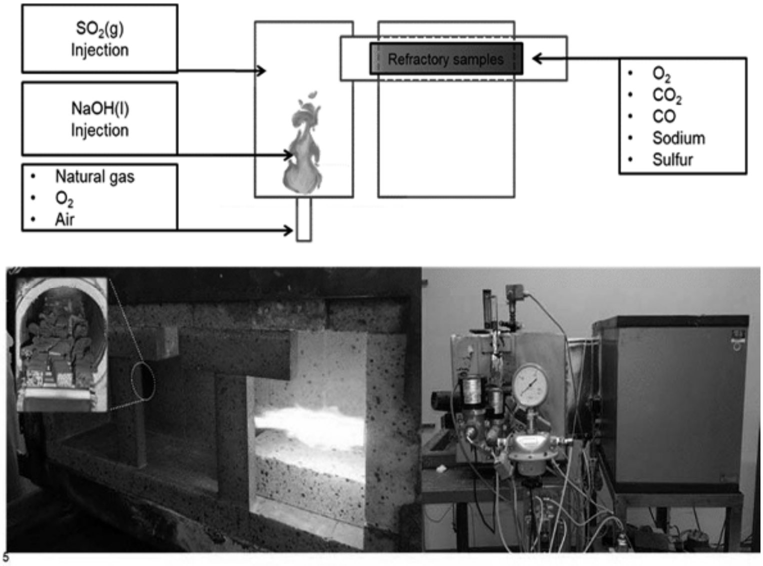

Figure 1. Experimental set-up to study behavior of regenerator refractory material exposed to well-defined flue gas composition (i.e. the oxidation state of the flue gas (CO/O_2 content), and content of alkaline and sulfur species) as a function of temperature.

Generally, in the top-zone of the regenerator chamber (see Figure 2), the refractory material should resist interaction with carry-over products comprising e.g. fine sand, fine cullet and decrepitating limestone and/or dolomite. No flue gas condensates are expected to be formed in this zone and therefore the choice of refractory material in this zone does not depend on oxidation state of the flue gas. Also for the hot-zone of the regenerator chamber (>1100°C) a similar flue gas behavior is expected for both oxidizing and reducing conditions. The predominant reacting gaseous species in this hot-zone are alkaline compounds. The main sodium species for both oxidizing and reducing conditions is NaOH. In case of reducing conditions, the evaporation rate of sodium from the batch blanket and glass melt might be slightly higher than at oxidizing conditions resulting in (slightly) higher sodium concentrations in the flue gas at reducing conditions.

In the condensation zone (800-1100 °C) of the regenerator chamber, the condensation products formed during cooling of the flue gas depend on the oxidation state of the flue gas. At oxidizing conditions, for soda-lime-silica glasses with salt cake as fining agent, the predominant flue gas condensation reaction is given by $2\ NaOH\ (g) + SO_2\ (g) + \frac{1}{2}\ O_2\ (g) \rightarrow Na_2SO_4\ (l,s) + H_2O\ (g)$. At reducing conditions, with no or limited O_2 present, the amount of Na_2SO_4 condensates is reduced and sodium is also present as NaOH and Na_2CO_3. At these reducing conditions, refractory should be resistant towards attack by a mixture of NaOH, Na_2CO_3 (+ Na_2SO_4). RHI indicates that at CO-levels exceeding 1.000 vol-ppm the most suitable refractory material is material composed of 97% MgO with direct MgO bonding and C_2S ($2CaO.SiO_2$) binder (Type ‘Anker DG1’) is applied. Basic products show excellent performance under these conditions whereas non-basic products, e.g. mullite-based products, are not suitable, due the formation of nepheline resulting in large volume changes.

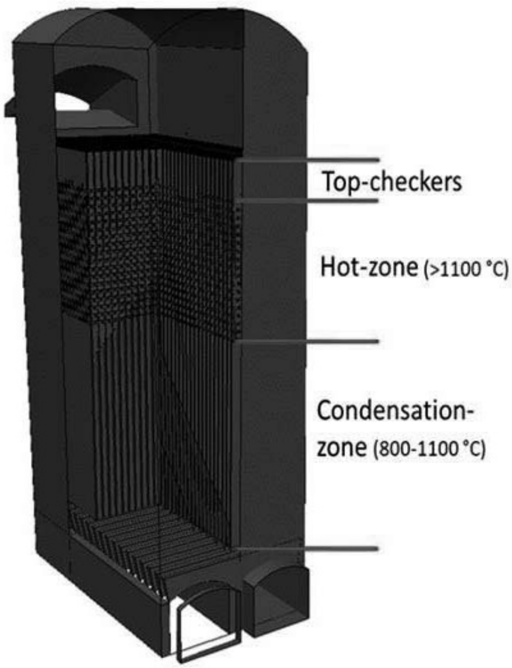

Figure 2. Schematic view of a single-pass regenerator with different zones having different requirements with respect to choice of refractory material.

An industrial example of the impact of reducing conditions on alkaline evaporation is shown by Figure 3. This figure shows the sodium evaporation rate for 3 similar furnaces with varying combustion conditions. From this figure it is clear that alkaline evaporation increases with increasing (local) CO content of the flue gas and the local flue gas velocities in the vicinity of the surface of the batch blanket and hot glass melt. In other words, excessive evaporation that might lead to intensified clogging and corrosion of refractory material in regenerator chambers can be controlled by optimizing combustion conditions avoiding amongst others high (local) CO-levels, temperatures and flue gas velocities.

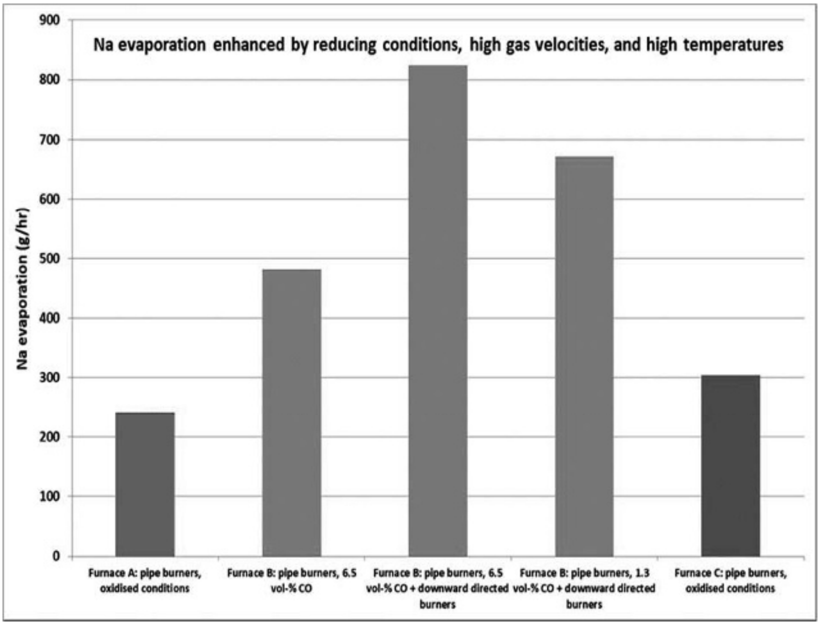

Figure 3. Sodium evaporation rate for 3 similar furnaces with varying combustion conditions.

REGENERATOR MODELING

Detailed 3D modeling of glass furnace regenerators is required in order to analyze whether the regenerator volume is efficiently utilized and whether heat recovery from the hot flue gases by the checker work and the subsequent heat transfer towards the combustion air can be improved. Simulation of the flow pattern in regenerators reveals any presence of dead zones and/or flue gas and combustion air recirculation areas, which have a strong negative effect on regenerator efficiency. Next to its dependency on regenerator dimensions, flue gas heat recovery is determined by the types of checkers applied in the regenerator, the connection of the burner ports to the regenerator, and the presence and location of air infiltration. The uniformity of the combustion air and flue gas flow distribution on each cross-section of the regenerator, and thus the regenerator efficiency, is very much determined by the ability of lateral flow (cross-mixing). Next to flow and temperatures, detailed regenerator modeling (in combination with industrial flue gas measurements) can be used to identify critical areas for fouling and clogging due to formation of condensates while cooling the flue gases.

The heat transfer, flue gas and combustion air flow of the single-pass regenerator as shown in Figure 2 is simulated. The checker-work was composed of closed chimney blocks and chimney blocks with mouse holes (see figure 4). For a proper validation of the regenerator model, an industrial measuring session was performed to measure/determine:

- Flue gas composition (both in the top and bottom of the regenerator chambers)
- Flue gas temperature (both in the top and bottom of the regenerator chambers)
- Flue gas volume flow (both in the top and bottom of the regenerator chambers)
- Air infiltration rate
- Combustion air preheat temperature
- Combustion air volume flow

- Structural heat losses from all regenerator chamber walls (see figure 5 for an example) as local heat losses will have an impact on local flue gas and combustion air temperatures (and thereby on regenerator efficiency).

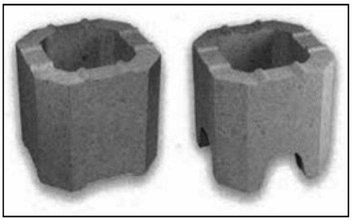

Figure 4. Examples of closed chimney blocks and chimney blocks with mouse holes

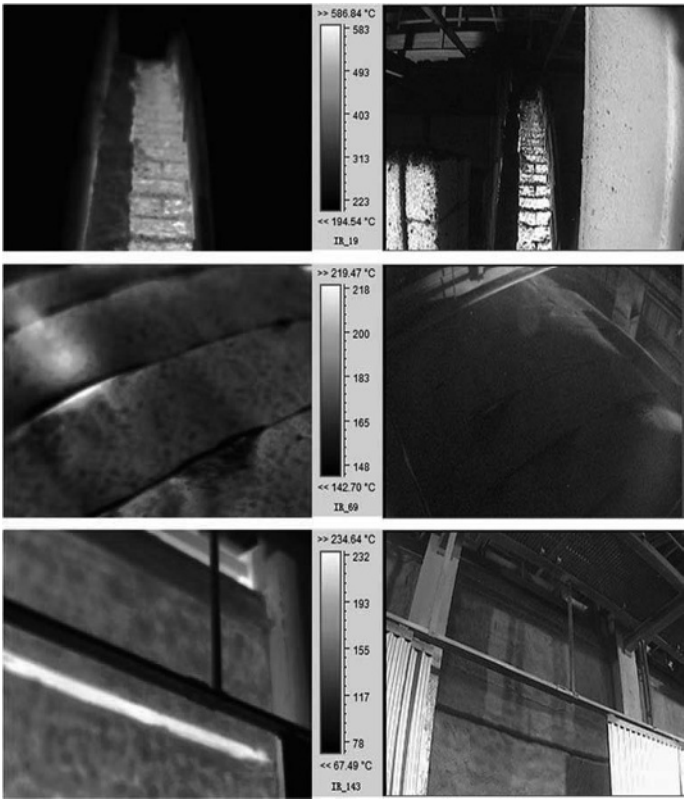

Figure 5. Outer wall temperature images at various positions of a regenerator chamber

As result of the regenerator simulations, figure 6a and 6b show the flow of hot flue gas (Figure 6a) and cold combustion air (Figure 6b) through the regenerator chambers. Based on these flow profiles (and 3D temperature fields) the following observations were made for this tall/narrow regenerator chamber:

- During the flue gas cycle, recirculation of flue gas in the dome of the regenerator chamber is observed affecting even distribution of flue gas flow over the cross-section of the regenerator chamber
- The hot flue gas flows by preference along the target wall downwards, specifically heating the vertical channels at the target wall side of the regenerator chamber
- The cold combustion air flows by preference in upward direction along the 'burner port wall'
- The preferential flow of hot flue gas and cold combustion air at opposite sides of the regenerator chamber leads to non-optimal heat exchange between flue gas and combustion air
- Chimney blocks with mouse holes support the temperature homogenization over the cross-section of the regenerator chamber (despite the preferential flows of combustion air and flue gas).

Based on these observations, design modifications for the regenerator chambers are discussed and will be evaluated from the perspective of improved thermal efficiency and reduced maintenance.

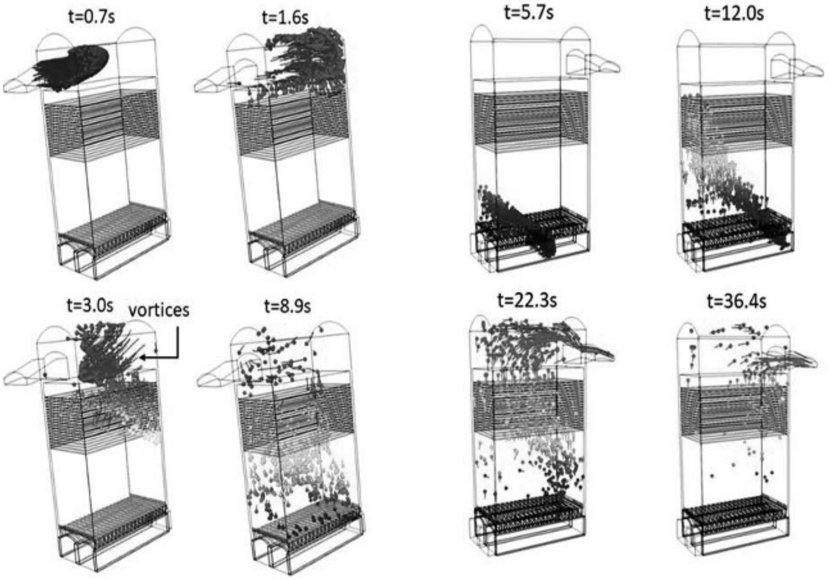

Figure. 6a and 6b: Flow of hot flue gas and cold combustion air through the regenerator chambers (the transport of flue gas and combustion air at different time intervals is shown)

CONCLUSIONS

This paper describes the use of detailed and fast simulation models for glass furnace regenerators to enable optimization of heat recovery from hot flue gases. The combination of detailed modeling with industrial measurements enables a complete analysis of the regenerator performance, including actual evaluation of flow pattern and temperature distribution due to air leakages. In addition the regenerator design, control (and minimization) of evaporation of volatile components from the batch blanket and hot glass melt condensing at the checker-work supports increased thermal regenerator performance over time with limited maintenance. Special care has to be taken in case of lowNOx firing conditions at which increased CO-levels can cause intensified condensate formation in regenerator chamber. Increased levels of alkaline and sulfur species in combination with ‘high’ CO-levels can cause an increase in checker-work corrosion. Experimental tools are available to assess the impact of flue gas composition on checker-work material and temperature. Simulation, industrial measurements, lab-facilities and extended refractory knowhow enables optimization of regenerator design and operation even at reducing conditions.

REFERENCES

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