Process controlled reduction of evaporation in glass furnaces

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The rate of evaporation of glass melt components is mainly determined by process conditions in the glass furnace, especially the combustion process has a large impact. From TNO evaporation studies semi-empirical relations have been obtained which can be used to predict the sodium evaporation from glass melts. TNO developed an evaporation model based on a combination of these semi-empirical relations, RCM (Rapid Combustion Model) and GTM (Glass Tank Model). This model has been used to predict and explain the different sodium evaporation rates in different soda-lime glass furnaces. The quantitative effect of temperature, gas velocity and gas composition on the sodium evaporation in these furnaces is estimated by a sensitivity analysis.

Introduction

Apparently identical glass furnaces might have totally different (dust) emission levels and different refractory corrosion problems. High evaporation rates of glass components from the glass melt and high carry-over rates of batch components are often the main reasons of high dust emissions and observed refractory corrosion problems. Well-known harmful consequences of high evaporation rates and high carry-over rates are high dust emissions, blocking of the regenerator chamber or flue gas channel and corrosion of checker works, silica crowns or burner blocks. To explain the observed differences between comparable furnaces a semi-empirical evaporation model was developed. This evaporation model can be combined easily with existing combustion models and glass tank models.

In this paper, the theoretical backgrounds of the model are described and the results of industrial validation tests in four more or less comparable soda-lime oxy-fuel glass furnaces are discussed.

Theoretical backgrounds

The semi-empirical relations used to the describe the results obtained from laboratory evaporation experiments are based on the Conradt [1] evaporation model, in which the evaporation rate (r) is described by the Langmuir equation:

$$r = \alpha_L \,.\, P .\, (M \,/\, [2p.R.T]\,)^{0.5}$$

$$\alpha_L = \alpha_R \,.\, \alpha_S$$

$$\alpha_R = e^{(-k \,/\, \{R.T\}\,)}$$

$$\alpha_S = Sh.D/L \,.\, (2p.M \,/\, [R.T]\,)^{0.5}$$

The evaporation rate can be simplified to:

$$r = (Sh.D.P.M \,/\, [L.R.T]) * e^{(-k/T)} \qquad (1)$$

Whereby

r = evaporation rate ($kg/m^2/s$)
α_L = Langmuir coefficient (-)
α_R = vaporization reaction part of Langmuir coefficient (-)
α_S = gas flow part of Langmuir coefficient (-)
Sh = Sherwood number(-)
D = diffusion coefficient (m^2/s)
P = partial equilibrium pressure of evaporated specie (Pa)
M = molecular mass of evaporated specie (mole/kg)
L = characteristic length for gas flow (m)
R = gas constant (8.3144 J/mole/K)
k = constant (K)
T = temperature of glass surface (K)

The Sherwood number is used to describe the mass transfer to a flowing medium. In case of a glass furnace in which the glass surface can be described as a flat plate, parallel to the flow:

$Sh = 0.332 . Re^{1/2} .Sc^{1/3}$ [6]

(Reynolds number = Re and Schmidt number = Sc).

The Sherwood number depends among other things on the gas velocity above the melt. The diffusion coefficient and partial pressure of volatile species are also related to the gas velocity. In practice the factor 1/T hardly contributes to the evaporation rate because of the relative large impact of $e^{(-k/T)}$.

The application of the Langmuir equation to predict the evaporation rates in industrial glass furnaces is rather complex. For that reason a simplified, semi-empirical relation was used to describe the evaporation rates from industrial glass furnaces.

$$r = K_1 . pH_2O^n . V^x . e^{(-k2/T)} \qquad (mg/s/m^2) \qquad (2)$$

Whereby

K_1 = constant ($mg/bar/m^3$)
pH_2O = water vapor pressure in atmosphere (bar)
V = gas velocity above melt (m/s)
n,x = constants (-)
T = glass temperature (K)
k2 = constant (K)

In case the water vapor pressure does not influence the evaporation process, constant n = 0. However in case of reactive evaporation the exponent n can be obtained from the reaction equilibrium constant.

<u>Example</u>:

X_2O (m) + H_2O (g) $\Leftrightarrow$ 2 XOH (g)

$k = (pROH)^2 / (pH_2O.[R_2O]) = A\ e^{\{-Ea/(R.T)\}}$ (3)

Whereby:

X = glass component
k = reaction equilibrium constant
A = constant of Arrhenius
R = gas constant (8.31 J/mole/K)
T = temperature (K)

In a reducing atmosphere containing CO the reaction between a glass component X and gaseous CO in the atmosphere may cause reactive evaporation also.

<u>Example</u>:

$X_2O + CO\ (g) \Leftrightarrow 2\ X\ (g) + CO_2\ (g)$

In that case formula 2 will be extended to:

$r = K_1 .\ pH_2O^n .\ V^x .\ e^{(-k2/T)} + K_3 .\ (pCO/pCO_2)^m .\ V^y .\ e^{(-k4/T)}$ (4)

One should keep in mind that the transport in the glass melt is not included in the equations (1) till (4). The transport in the melt will be of major importance in case:

1. The concentrations of a certain component in the melt are relatively low,
2. Depletion occurs. Depletion may occur when the temperature of the melt is homogeneously and there is no forced convection (i.e. bubbling).
3. Formation of (dynamic) foam. Due to the fining process (usually the dissociation of sodium sulfate) gas-bubbles are formed by which a foam layer is formed at the surface layer of the melt [2]. The foam layer is continuously refreshed by components of the glass melt. The evaporation rates of this dynamic foam layer are also enhanced because of the relative large surface area and the relative high temperatures of this foam layer.

For different types of glass and different glass components, values for the constants K1, K2, K3, K4, n, m and x in the formulas 2 and 4 were obtained.

Industrial validation tests

In this study, only modeling of sodium evaporation has been carried out to demonstrate the validity and application of such evaporation model for understanding emissions and evaporation processes in industrial furnaces. In the previous sections it was shown that glass melt temperature, gas velocity and composition of glass melt and furnace atmosphere are key parameters in the kinetics of evaporation of glass compounds. For oxygen fired soda-lime-silica glass furnaces, modeling of sodium evaporation has been carried out [3]. Modeling has been performed for these comparable furnaces, all producing the same type of glass, but for different burner settings. Table 1 shows some process data of these furnaces. Although, the furnaces are of the same design type and the same glass composition and raw materials are similar, the specific dust and sodium emissions are very different. As the evaporation model results show, the burner settings and the reducing/oxidizing combustion conditions greatly effect the evaporation of sodium species. The quantitative effect of temperature, gas velocity, water vapor pressure and partial CO pressure on the sodium evaporation in these furnaces is estimated by a sensitivity analysis. These parameters vary between:

- Glass surface temperature (T) : 1420 – 1520 °C
- Water vapor pressure (pH2O) : 0.5 – 0.65 bar
- Gas velocity above glass surface (v) : 0.5 – 0.9 m/s
- CO levels in atmosphere : 0 – 7 vol.-%, dry

Figure 1 shows the effect of reducing flames on the Na evaporation. Only 1 % CO in the atmosphere means 50 % higher sodium evaporation rate. In case of 3.5 % CO the Na evaporation rate is even doubled. Obviously, highly reducing flames should be avoided. The effects of temperature, gas velocity and water vapor pressure are given in figure 2. The influence of temperature variations appears to be of major importance. A temperature increase from 1470 till 1520 °C results in a doubling of the sodium evaporation rate, an increase of the gas velocity from 0.7 till 0.9 m/s means 25 % more evaporation and variations in water vapor pressure between 0.5 and 0.65 bar hardly influences the Na evaporation.

Figure 3 shows the results of the industrial measurements. Obviously, changes in the position and type of burner and the oxygen-natural gas ratio (determining p_{O2} and p_{CO} vapor pressures) will cause large differences in dust emissions and sodium evaporation. The gas velocities and glass melt surface temperatures in these furnaces are calculated with a CFD model [4]. The modeling results for NaOH evaporation and Na_2O losses show the same trend as the measurements. The evaporation loss of Na_2O from the surface area with the highest temperature (hot spot) has been calculated for these furnaces. According to the values in figure 4, about 60 to 80 % of the sodium evaporates from this area, which is only 30 % of the total melt surface area.

It can be concluded that there is a good correlation between the sodium evaporation modeling results and industrial evaporation measuring results in 4 different glass furnaces.

Table 1: Operational conditions of soda lime glass furnaces and measured particulate emissions

Furnace burner arrangement no.	1	2	3	4	5
Average glass melt surface temperature in ^oC	1494	1494	1511	1511	1453
Surface area in m^2	39	39	39	39	60
Na_2O content of glass in wt%	16.5	16.5	16.5	16.5	16.5
Water vapor pressure in furnace atmosphere in 10^5 Pa	0.6	0.6	0.6	0.6	0.6
Gas velocity above melt in m/s	0.5	0.5	0.7	0.7	0.7
Burner type	tube-in-tube	sheet flame	sheet flame	sheet flame	staged
Low Momentum/high momentum	high	high	high	high	low
Oxygen pressure above melt in 10^5 Pa	0.03	0	0	0	0.005
CO-pressure above melt in 10^5 Pa	0.001	0.065	0.065	0.013	< 0.001
Burner horizontal or directed to glass melt surface	horizontal	7^o directed	7^o directed	7^o directed	horizontal
Dust emission in kg/t glass	0.276	0.398	0.559	0.485	0.189
Na_2O emission in kg/t glass	0.096	0.190	0.315	0.262	0.087
NaOH concentration in furnace atmosphere in Pa	21.8	26.0	36.0	38.5	9.9

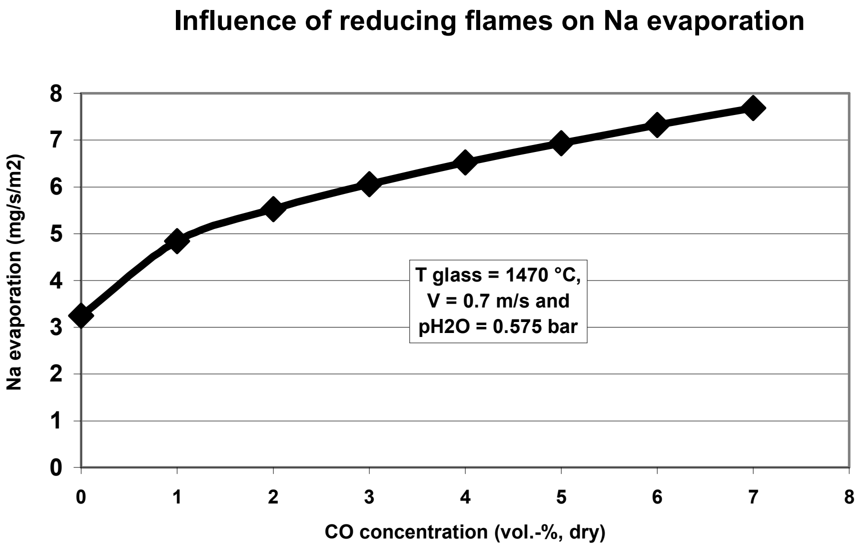

Figure 1: Influence of reduced flames on sodium evaporation from glass melts

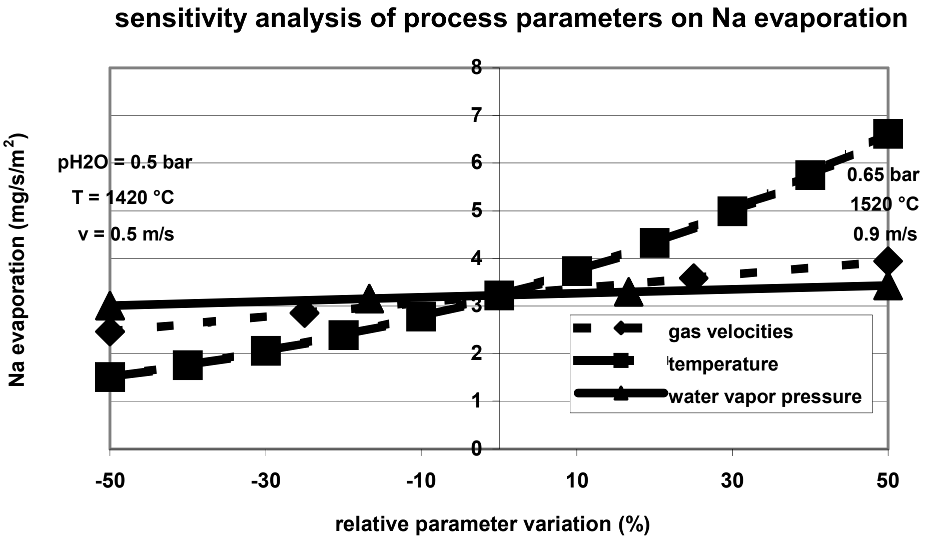

Figure 2: Sensitivity analysis of different process parameters on the sodium evaporation

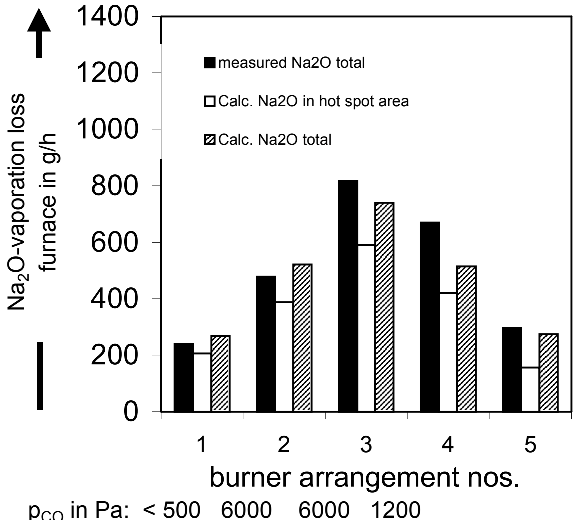

Figure 3: Na2O evaporation losses from 5 different oxy-fuel soda-lime glass furnaces: results of modeling and measurements

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