Thermal heat conductivity of glass forming batches

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Abstract

The current paper reports on the use of a numerical-experimental technique for the determination of the effective thermal heat conductivity of glass forming batches. Next to a discussion of the numerical-experimental technique, values for the thermal heat conductivity of silica sand layers are presented.

Introduction

Mathematical simulation of the glass melting process is often used as a tool for process trouble shooting and optimisation of the process settings and designs of glass melting furnaces. The success of the use of simulation models depends on the accuracy of both the (sub) model(s) and the model input parameters. Today, the most important sub-model requiring a more accurate description of its properties is the glass forming batch blanket model. According to CFD (Computational Fluid Dynamics) simulation models for glass furnaces, the dimensions (i.e. thickness and length) and the thermal properties of a glass forming batch[1] have a large impact on the calculated temperature distributions and flows in the melting tank. However, the current mathematical glass batch models only provide a rough description of the behaviour of glass batches, which is mainly caused by the lack of accurate values for glass batch properties.

The mathematical simulation of the behaviour of glass batches requires solving the conservation equations for mass, energy and momentum. The thermal energy equation of a glass batch is described by equation 1, in which ρ is the batch density, c_p is the heat capacity of the glass batch, T is the batch temperature, t is the time, $\mathbf{v}$ is the moving velocity of the glass forming batch, λ_{eff} is the so-called effective thermal heat conductivity and S is the net source term for endo- and exothermic batch reactions.

$$\rho c_p \frac{\partial T}{\partial t} = -\rho c_p \left(\mathbf{v} \cdot \nabla T\right) \nabla \cdot \left(\lambda_{\text{eff}} \nabla T\right) + S \qquad (1)$$

The heat penetration in a glass batch is determined by a combination of three modes of heat transfer:

- conductive heat transport by mutual contact between solid particles and between solid particles and liquid phases,
- radiative heat transport through the transparent liquid phases, and
- heat transfer between ascending gasses (resulting from batch reactions) and the surrounding batch particles and liquid phases.

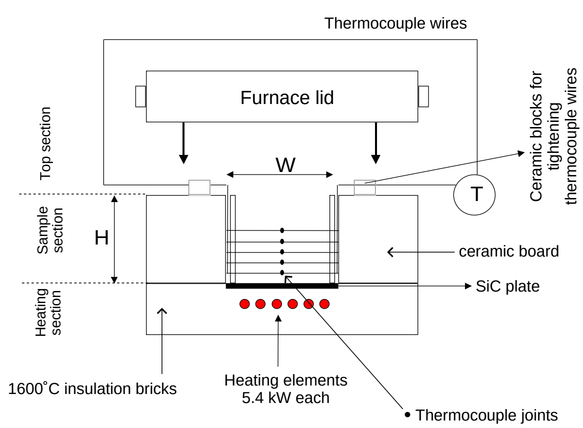
Since (experimental) discrimination between these modes of heat transfer in glass forming batches is complex, the heat penetration in a glass batch is described by an effective thermal heat conductivity λ_{eff}, which encloses the contributions of all three modes of heat transfer. From experimental studies on the heat penetration in glass batches [1, 2, 3, 4], it appeared that the effective thermal

[1] In the continuation of the current paper, the term 'glass forming batch' will be denoted as 'glass batch'

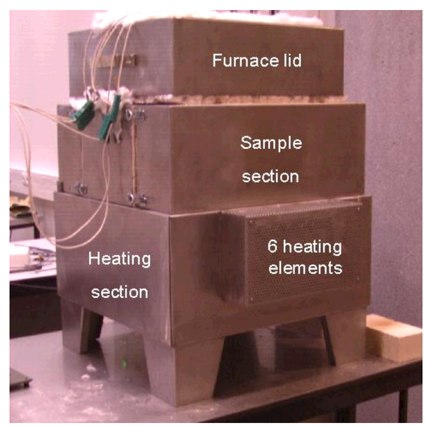
heat conductivity is strongly dependent on the concentration C of melt phases in the melting glass batch. This means that $\lambda_{\text{eff}} = \lambda_{\text{eff}}(C, T)$. For a cullet free batch, the amount of melt phase is mainly dependent on the amount of dissolved silica in the primary formed melt phases. Because silica dissolution is both temperature and time dependent, $C = C(T, t)$, the effective thermal heat conductivity of a glass forming batch is dependent on the total temperature history, $\lambda_{\text{eff}} = \lambda_{\text{eff}}(T, t)$. A technique that is able to deal with this type of time-dependent behaviour of the glass batch is a numerical-experimental technique. In the current paper, a numerical-experimental approach is discussed which can determine values for the effective thermal heat conductivity of glass batches with a limited set of parameters. The accuracy and reproducibility of this technique is discussed by the determination of the thermal heat conductivity of silica sand layers. The method is validated by comparing values for the thermal heat conductivity of silica sand with literature data.

Experimental set-up

The use of the numerical-experimental technique requires an experimental set-up from which the time- and temperature dependent behaviour of glass batches can be derived. Figures 1(a) and 1(b) show the experimental set-up that has been developed for measuring temperatures at different positions in a glass batch.



(a) Scheme of the experimental set-up



(b) Photo of the experimental set-up

Figure 1: Experimental set-up for measuring heat penetration in glass batches

The experimental set-up consists of 3 sections, i.e. the heating section, the sample section and the top section. The outer dimensions of the experimental set-up are 600mm x 600mm x 800mm. The heating section contains 6 SiC elements with a maximum power of 5.4kW each and is insulated with 1600°C insulation bricks. The aperture W of the sample section is 250mm square and the height H of this section 220mm. The aperture is separated from the heating section by a SiC plate, which is heated by SiC elements. On top of the SiC plate the raw material batch is charged. The sample section is insulated at the sides with ceramic board. The width of the aperture and the thickness and properties of the ceramic insulation board are choosen such that the heat penetration in the glass batches can be regarded as one dimensional (vertical) heat transport. In the sample section a square of insulation bricks is made through which 0.35mm S-type thermocouple wires are guided. The joint of these thermocouple wires are positioned in defined vertical distances at the center of the aperture. The position of the thermocouple wires is fixed by tightening these wires

in ceramic blocks located on top of the sample section. On top of the sample section a furnace lid, which is composed of insulation wool, is located. The temperature in the bottom section of the furnace is controlled by a thermocouple which is located close to the SiC plate.
The sample section is partly filled with the raw material batch at room temperature in order to avoid vertical displacement of the thermocouple wires as much as possible. After filling the sample section the furnace lid is put on top of the sample section and the set point of the temperature close to the SiC-plate is set to the desired temperature. The temperature at different positions in the glass batch is recorded as a function of time.

Numerical-experimental technique

By comparison of the axial (z) and radial (r) temperature gradients in silica sand batches in the experimental set-up, it appeared that the heat transport in these batches can be regarded as one dimensional. The heat penetration measurements in the silica sand batches can be simulated by solving the one dimensional thermal energy equation given by equation 2. For the experiments with silica sand, both the **v**-field and the source term S for chemical reactions equals zero. This reduces equation 1 to equation 2. However, because the effective thermal heat conductivity is temperature (and therefore position) dependent, its value can not be determined explicitly from this equation.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{\text{eff}} \cdot \frac{\partial T}{\partial z}\right) \tag{2}$$

For the estimation of the effective thermal heat conductivity from the heat penetration measurements, a numerical-experimental technique [5] has been used. This technique consists of three parts, i.e. the experiment, the mathematical simulation of the experiment and an estimation algorithm.

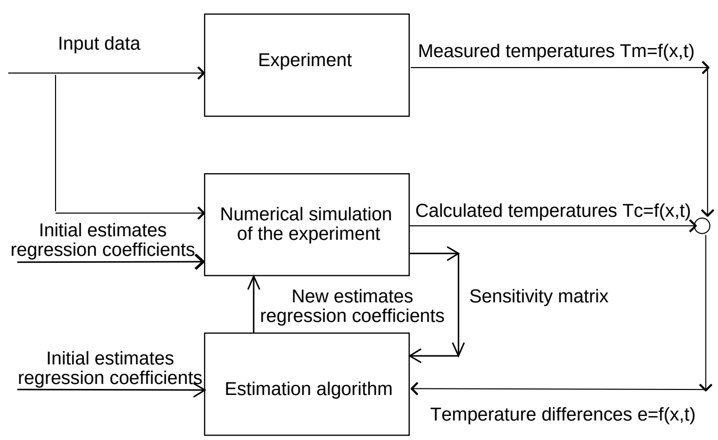


Figure 2: Scheme of numerical-experimental technique according to Op den Camp et al. [5]

Below, a short description of this technique is presented:

The experiment concerns the measurement of the temperatures at different positions in the silica sand batch. The output of the experiment is a matrix of measured temperatures at different positions in the glass batch as a function of time, **Tm(z,t)**.

The fixed input data for *the numerical simulation of the experiment* are 1) the thickness of the silica sand batch, 2) the initial temperature of the silica sand batch, 3) the time-dependent temperatures at the boundaries of the silica sand batch and 4) values for the batch density and the heat capacity. Next to these fixed input parameters, also a model describing the temperature dependent effective thermal heat conductivity of the glass batch has to be defined. For a silica sand batch, a 1^{st} order temperature dependency of the thermal heat conductivity is assumed [1].

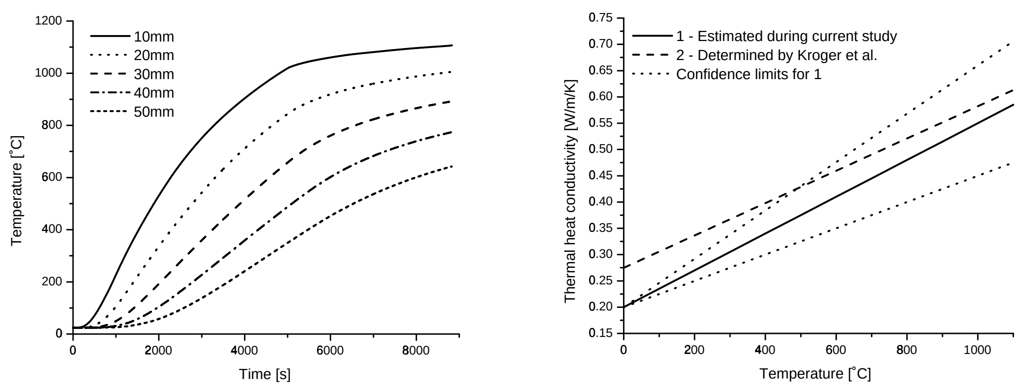
For the calculation of the temperatures at different positions in the silica sand batch as a function of time, **Tc(z,t)**, an initial estimate for the regression coefficients a and b from equation 3 are required.

$$\lambda = a + b \cdot T \tag{3}$$

Because the initial estimates for the regression coefficients a and b will deviate from the real values for these coefficients, the calculated temperatures will differ from the measured temperatures. *The estimation algorithm* minimises the temperature difference matrix e with respect to the unknown regression coefficients a and b by a least squares approach. This minimisation procedure requires a sensitivity matrix which quantifies the sensitivity of the calculated temperatures for a small change of the estimated regression coefficients. The estimation procedure is repeated until the change in the new estimated regression coefficients is less than an a priori defined tolerance.

Results

Figure 3(a) shows the measured temperatures in a silica sand batch at a level above the SiC-plate of 10mm, 20mm, 30mm, 40mm and 50mm. The time-dependent temperature at both 10mm and 50mm act as time-dependent boundary conditions for the numerical simulation of the heat penetration process. From these measured temperatures, the regression coefficients a and b from equation 3 have been estimated by using the numerical-experimental technique.



(a) Measured temperatures at different positions in a silica sand batch

(b) Thermal heat conductivity of silica sand

Figure 3: Measured temperatures in silica batch and thermal heat conductivity of silica sand

Figure 3(b) shows the calculated thermal heat conductivity of the silica sand batch. An uncertainty analysis showed that an error in the positioning of the thermocouples in the silica sand batch is the main source for the uncertainty in the estimated thermal heat conductivity. In figure 3(b) the values for the thermal heat conductivity of the silica sand batch is estimated with a experimental determined error in the positioning of the thermocouples of $\pm$1mm. The uncertainty in the effective thermal heat conductivity is approx. 18% at 1100°C. Figure 4 shows the temperature dependent thermal heat conductivity of three different types of silica sand. These silica sand batches differ in the particle size distributions. The thermal heat conductivity for the types 2 and 3 have been determined twice. The temperature dependency of the thermal heat conductivity b derived from the five measurements varies in the range of $3.06 \cdot 10^{-4}$ W m^{-1} K^{-2} to $3.56 \cdot 10^{-4}$ W m^{-1}K^{-2}, and the regression intercept a varies in the range of 0.08 W m^{-1} K^{-1} to 0.11 W m^{-1} K^{-1}. Kröger [1] presented a value of $3.01 \cdot 10^{-4}$ W m^{-1} K^{-2} for the temperature dependency and a value of 0.18 W m^{-1}K^{-1} for the intercept.

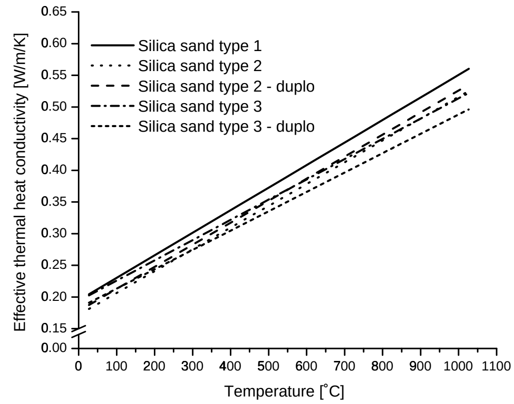


Figure 4: Thermal heat conductivity of three silica sand types

Conclusions and outlook

With the numerical-experimental approach, described in the current paper, values for the temperature dependent thermal heat conductivity of silica sand have been determined with an uncertainty of approx. 18% at 1100°C. The measured thermal heat conductivity shows a (slight) deviation with literature data. This deviation may be caused by differences in particle shapes and packing of the silica batch. The numerical-experimental technique is used for estimation of the effective thermal heat conductivity of glass batches. However, the estimation of the effective thermal heat conductivity for glass batches is more complex than for silica sand batches, due to:

- the presence of a source term S in equation 2 describing endo- and exothermic batch reactions
- the addition of a 3^{rd} order term in equation 3 describing the contribution of radiative heat transport through transparent melt phases to the effective thermal heat conductivity.

The study described in this paper is a part of an extended research study, which focusses on both the chemical and thermal behaviour of glass batches. During this study also the kinetics of the main batch reactions have been studied. Combining these kinetics with their reaction enthalpies provides an expression for the temperature dependent source term S.

When the effective thermal heat conductivity of glass batches and the source term for chemical reactions are known, a complete description of the thermal behaviour of glass batches is given.

References

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