Original Paper

Electromagnetic force in electric glass melting

Otto R. Hofmann

Fachbereich Grundlagenwissenschaften, Fachhochschule Jena, Jena (Germany)

Electromagnetic effects occur in electrically heated glass melts. Sometimes this fact causes disadvantages but it also offers the chance to influence the glass flow beneficially. A Lorentz force can be generated by a strong external magnetic field called "Fremdfeld" (foreign field). The Lorentz force in the "Eigenfeld" (eigenfield) that is caused by the magnetic field around the current density in the glass can be neglected. A specific Lorentz force in the "Eigenfeld of the electrode" occurs in electric glass melting using rod electrodes and results from the magnetic field around these electrodes.

The numeric JENA-HLX code was employed to calculate the current density distribution for complex voltages and the temperature-dependent electric conductivity. The magnetic field was built up according to the Biot-Savart law.

A first computer calculation shows that the Lorentz force will become the second driving force besides buoyancy near electrodes, provided electrode currents are about 800 A or higher. A second numeric trial dealt with a side-wall, a bottom and a top electrode in R-S-T connection. Here the most significant effect occurred at side-wall electrodes, where horizontal velocities increased.

The third test was carried out to learn more about the Lorentz force in an electrically heated crucible. Here the most interesting effects were to observe when a Fremdfeld was applied to the electrically heated fluid. In modelling external horizontal and vertical magnetic fields, the resulting fluid flow depends on the mutual orientation and the phase shift between current density and magnetic field. For instance, the forced glass melt rotation around the electrodes is reversed if this phase shift changes from 0° to 180°. To sum up, the Lorentz force offers various opportunities to control the glass flow.

1. Introduction

In glass melting technology up to now there is insufficient understanding of electromagnetic effects that occur in the case of electrically heated glass melts. Sometimes this fact causes disadvantages but it also offers the chance to influence the glass flow in the desired direction. Because of new products, new melting techniques and the growing importance of the electric energy in the future, the object of this paper is to discuss the different aspects of the electromagnetic Lorentz force in molten glass.

2. Special kind of Lorentz force

It is quite known that there are two ways to generate an electromagnetic force in fluids:

a) A Lorentz force can be generated by an external magnetic field that is called "Fremdfeld" (foreign field). There is some experience in physical modelling and practice of glass technology concerning that method [1 to 3]. An effective electromagnetic force results from strong magnets, e. g. right and left of the feeder channel.

b) The Lorentz force in the "Eigenfeld" (eigenfield) is generated by the current density $\vec{j}$ in the glass and the magnetic field $\vec{B}$ around $\vec{j}$ (and created by $\vec{j}$). According to [4] in glass melting this force is rather small and can be neglected. It may be important in other fluids (metal) which have high electric conductivity.

The second way mentioned was discussed by Stanek [4]. But it is wrong to state that the Lorentz force in glass melting technology and modelling can be totally neglected. A specific kind of that force occurs in electric glass melting using rod electrodes. It must be considered in mathematical modelling and explains some technological effects of the melting practice.

This Lorentz force in the Eigenfeld of the electrode [5 and 6] is caused in the following way: there is the electrode current I, which is the origin of the magnetic field $\vec{H}$ and the flux density $\vec{B}$, concentric around the electrode. These quantities form a maximum at the electrode dip and a minimum at the top position. The current density j flows radially into the glass bath. The vector product $\vec{j} \times \vec{B}$ is the Lorentz force density $\vec{f}_{\mathrm{L}}$ discussed here.

In a prior paper about that topic [5] we still assumed that the magnetic flux density $B = \mu H$ is concentric around the dipping electrodes $B(r) = \mu\, I_{\mathrm{E}}/(2\pi\, r)$ and decreases linearly from the electrode dip to the electrode top coordinate. The three-dimensional current density distribution was calculated by the analytic solution of the electric potential equation (Laplace type) around finite rod electrodes.

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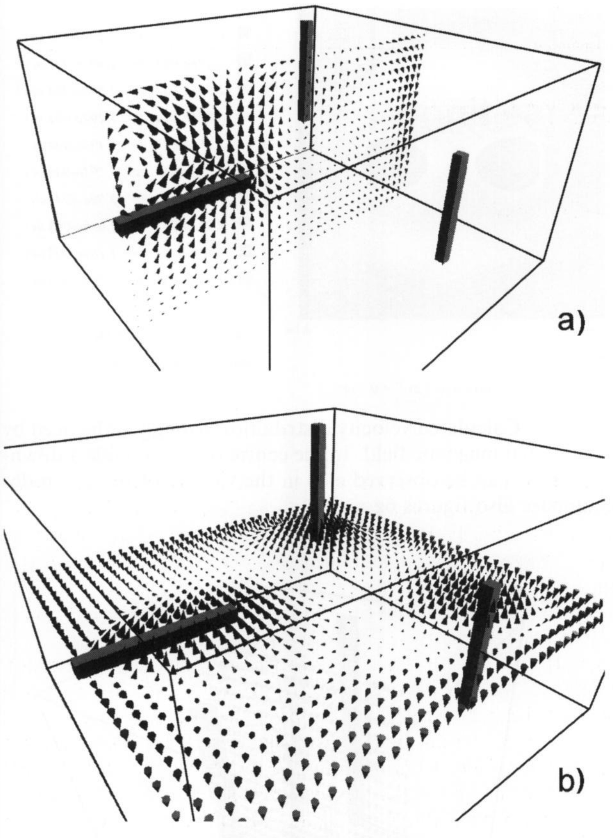
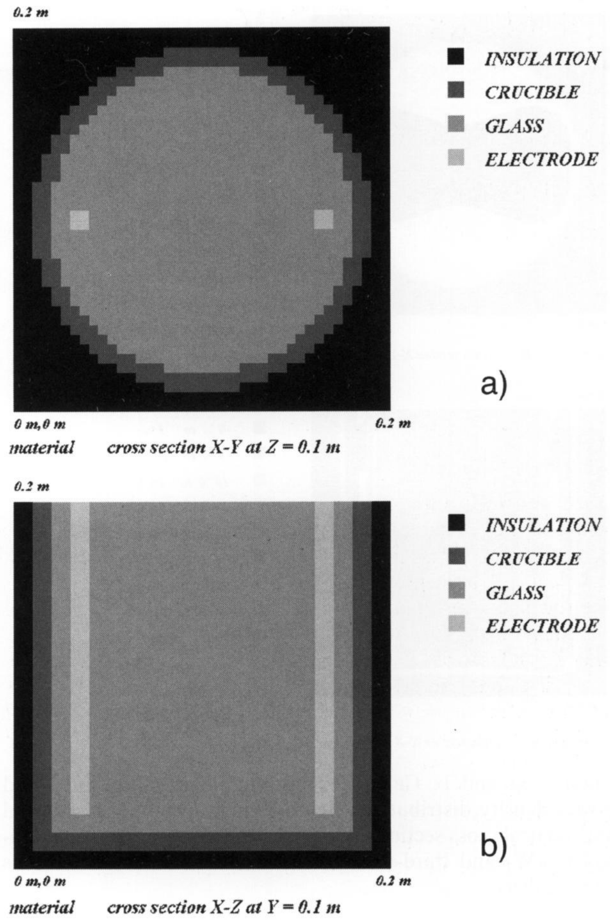


Figures 1a. and b. Effect of the Lorentz force on the glass bath velocity near two vertical electrodes and a horizontal one. Figure a) shows a vertical and figure b) a horizontal cross section area. The magnitude is symbolized by the thickness of the velocity arrows. The side-wall electrode pumps the glass from the dip to the top.



Figures 2a and b. Simulation of electric, temperature and velocity fields in glass heated by two electrodes in a crucible. Geometry and discretization of the (0.2 × 0.2 × 0.2) m^3 crucible; a) $x-y$ section, b) $x-z$ section.

In the present study we employ the numeric JENA-HLX code to calculate the current density distribution by the electric potential equation (Poisson type) for all kinds of electrodes, geometry, complex voltages and temperature-dependent electric conductivity. The three-dimensional magnetic field in the present paper is generated by the more rigorous Biot-Savart law $\mathrm{d}\vec{H}(r) = (\vec{j} \times \vec{r})\,\mathrm{d}V/(4\pi r^3)$ which is the solution of the governing differential equation rot $\vec{H} = \vec{j}$. In that way H and B are results of the electrode currents and the glass bath current density distribution. All the field quantities mentioned have complex amplitudes.

A further discussion of the meaning of the Lorentz force f_L in electric glass melting may be helpful because there are some statements that f_L has only a slight impact on the glass bath velocities near electrodes [4, 7 and 8].

The aim of this paper is to demonstrate the chance which results from employing magnetohydrodynamics in glass technology rather than to show the role of the electromagnetic force concerning modelling and electric melting technology.

3. Computer experiments

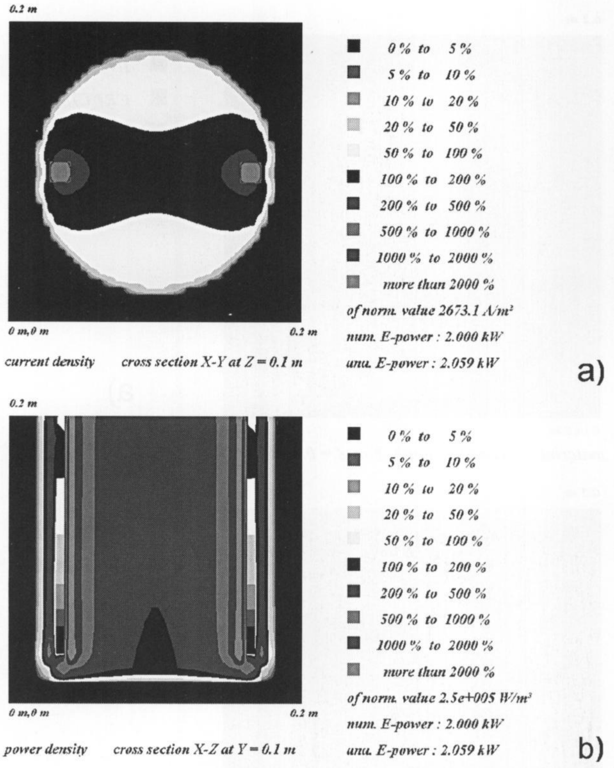
Some numeric trials were carried out to study the effects of the Lorentz force $\vec{f}_\mathrm{L}$. The first one uses a three-parallel electrode triangle configuration in R−S−T connection. For a given lead silicate glass a constant electric power is required [9]. Of course it depends on the temperature (or better on the electric conductivity) which current-voltage constellation occurs. And indeed buoyancy is the driving force for the free convection of glass flow.

However, in the vicinity of electrodes the Lorentz force becomes the second driving force if there are electrode currents of about 800 A and higher. The calculations were done using a coupled electric-temperature-velocity iteration with fixed boundary temperatures and power-constant control.

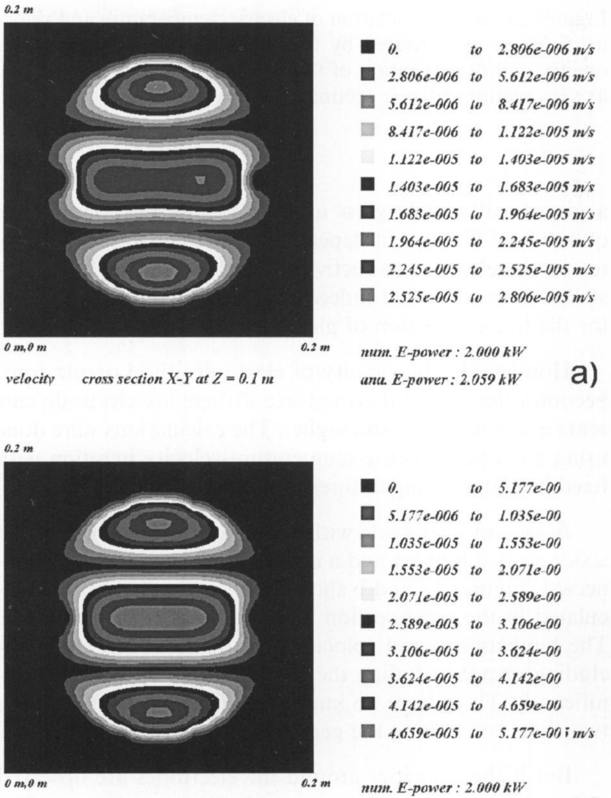
A second trial deals with a different geometry. We had a side-wall, a bottom and a top electrode also R−S−T connected. Figures 1a and b show the velocity distribution calculated in the cross section area of the side-wall electrode. The temperature and velocity field distributions either including or not including the Lorentz force do not vary significantly. There were no important differences between the two cases concerning the general field distribution.

But if the velocities around the electrodes are observed in detail, important differences and effects can be seen. The calculated differences including the Lorentz force are as follows:

- For the modelled bottom electrode there is a 30 % higher upstream velocity generated by f_L.



Figures 3a and b. Calculated current density (figure a) and power density distribution (figure b) in respectively horizontal and vertical cross section areas. An electric power constant control (2 kW) and third-order temperature boundary conditions were realized.



Figures 4a and b. Calculated velocity distributions without (figure a) and with Lorentz force (figure b). By including f_L the maximum glass velocity increases from 2.8 to 5.2 × 10^{-5} m/s.

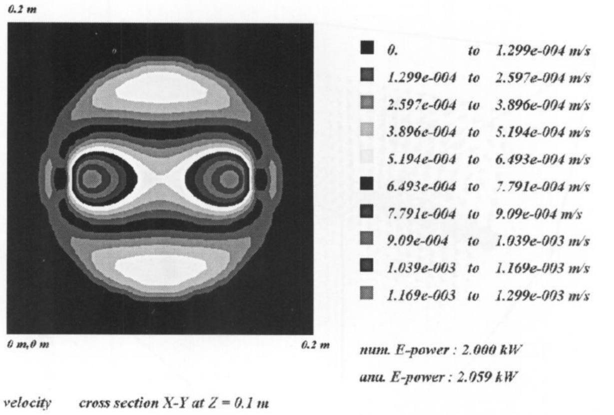
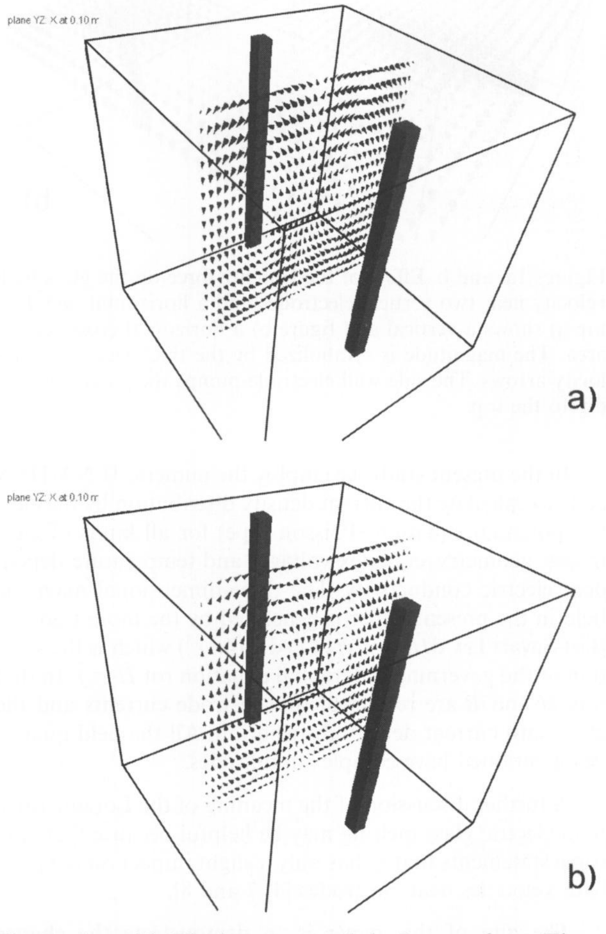
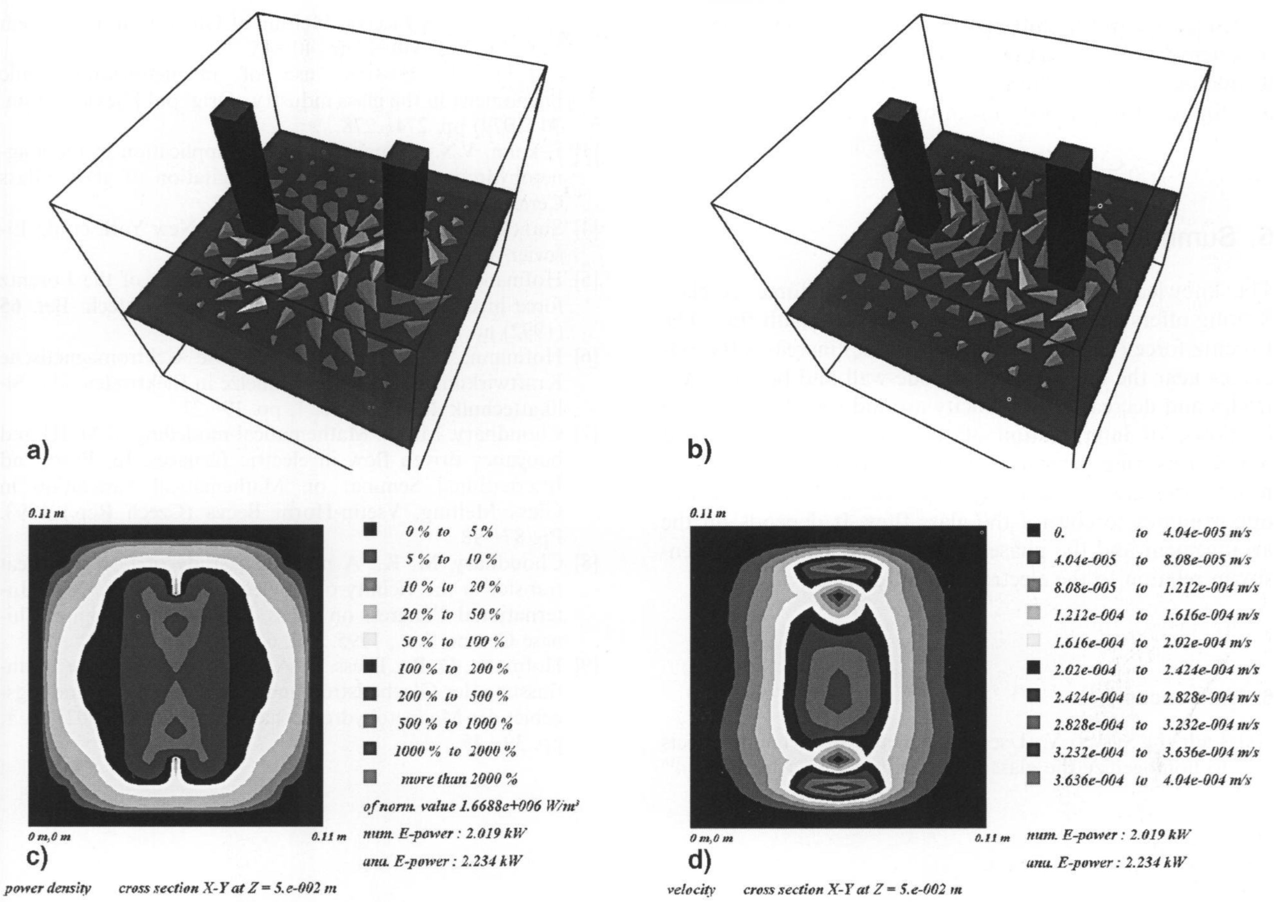


Figure 5. Calculated velocity distribution strongly influenced by an external magnetic field. In the centre of the crucible a downward flow can be observed also in the vicinity of the electrodes (compare also figures 6a and b).



Figures 6a and b. The buoyancy and the Lorentz force (Eigenfeld of the electrodes) are responsible for the upward velocity in the central area (figure a), the Lorentz force (Fremdfeld) forces a downward flow (figure b).

- For the top electrode the maximum upstream velocity decreases in our example by 30 %. This is an explanation for the good melting characteristics of top electrodes.
- But the most significant effect is shown by the electromagnetic force at side-wall electrodes where we observe extremely increased horizontal velocities.



Figures 7a to d. With external magnetic fields the fluid velocities depend on the mutual orientation and on the phase shift between $\vec{j}$ and $\vec{B}$. Here a rotation around the dipping electrodes is observed (figure a). This rotation is reversed (figure b) if the phase shift changes from 0° to 180°. For more information figure c) shows the power density distribution and figure d) the velocity magnitudes.

The effect of f_L within an electrically heated crucible is now considered. The location of the two electrodes and the material discretization may be taken from figures 2a and b. The crucible contained a lead silicate glass melt. For all calculations we realized a constant electric power control $P = 2$ kW.

The results of the calculated current and power density distribution in the glass and in the electrodes are shown in figures 3a and b. The electrode current was about 60 A, the maximum magnetic flux density about 0.0013 Vs/m^2 and the maximum Lorentz force density about 15 N/m^3. By including f_L into the calculation the maximum glass velocity in the crucible increased from 2.8 to 5.2×10^{-5} m/s. In figures 4a and b the velocity distribution in a cross section at half the height of the crucible is shown. Between the two electrodes on the left and on the right an upstream area is observed. Symmetrically two downstream areas occur (compare also figure 6a).

4. Employing an external magnetic field

Finally we discuss the effects which are to observe applying an external magnetic field (Fremdfeld) to an electrically heated fluid. In the past research work was done [1 to 3] using physical tank modelling and some results measured in hot glass. One of the aims of these investigations was to find out whether electromagnetic effects can cause stirring in feeder channels. Using mathematical modelling make it easier to evaluate the effects intended.

To show the general mass flux behaviour we assume salt water of different conductivity and molten glass in rectangular or cylindrical crucibles. The current density j flows from one electrode to the other determining the direction of j. The direction of the external B-field may be varied. It depends on where the north and the south poles of the external B-field are placed.

At first we discuss the behaviour of a lead silicate glass melt in the cylindrical crucible used before (figures 2a and b). An external and horizontal magnetic field was applied crossing the main electric current density vector. As a result of the calculation the velocity field changed completely (figure 5). Now a downstream flow (maximum velocity 1.3×10^{-3} m/s) occurs in the centre of the crucible. The differences are shown in figures 6a and b.

In modelling external magnetic fields the resulting fluid velocities depend on the mutual orientation and the phase shift between $\vec{j}$ and $\vec{B}$. To learn more about possible effects, B was arranged in the direction of the electrodes. The flow pattern is shown in figures 7a and b. We notice a rotation of the fluid around the dipping electrodes. This rotation is reversed if the phase shift between the electric and magnetic flux density vectors changes from 0° to 180°. For more information figure 7c shows the power density distribution and figure 7d the velocity magnitudes.

5. Summary

The knowledge about the electromagnetic force in glass melting offers chances to influence the glass bath flux. The Lorentz force (Eigenfeld of the electrode) increases the velocities near the dip positions of side-wall and bottom electrodes and decreases the velocity around top electrodes. So it allows for interpreation of the cause of corrosion and different melting behaviour. The Lorentz force (Fremdfeld) results from an external magnetic field and offers various opportunities to control the glass flow. It depends on the arrangement and the phase shift of the magnetic flux density in relation to the electric current density.

6. References

[1] Ladr, I.; Süsser, V.: Use of magnetohydrodynamic effects to homogenize the glass melt. (Orig. Czech.) In: Proc. 4th Conference on Electric Melting of Glass, Usti nad Labem (CSSR) 1974. Vol. 1, pp. 40–45.
[2] Carbon, J.: Possible use of magnetohydrodynamic phenomena in the glass industry. (Orig. pol.) Szklo Ceram. **30** (1979) pp. 274–278.
[3] Fekolin, V.N.; Stupak, F. A.: The application of the magnetohydrodynamic effect to the agitation of glass. Glass Ceram. **41** (1984) no. 12, pp. 10–12.
[4] Stanek, J.: Electric Melting of Glass. New York et al.: Elsevier, 1977. Pp. 269–272.
[5] Hofmann, O. R.; Philipp, G.: Importance of the Lorentz force in electrically heated glass melts. Glastech. Ber. **65** (1992) no. 5, pp. 142–149.
[6] Hofmann, O. R.; Kaliski, H.: Die elektromagnetische Kraftwirkung auf die Glasschmelze in Elektrodennähe. Silikattechnik **42** (1991) no. 1, pp. 19–21.
[7] Choudhary, M. K.: Mathematical modelling of MHD and buoyancy driven flow in electric furnaces. In: Proc. 2nd International Seminar on Mathematical Simulation in Glass Melting, Vsetin-Horni Becva (Czech Rep.) 1993. Pp. 87–98.
[8] Choudhary, M. K.: A modelling study of flow and heat transfer in the vicinity of an electrode. In: Proc. XVII International Congress on Glass, Beijing 1995. Beijing: Chinese Ceram. Soc., 1995. Vol. 6. Pp. 100–107.
[9] Hofmann, O. R.; Thess, D. A.: Elektromagnetische Beeinflussung der Glasbadströmung – Ein neues Anwendungsgebiet der Magnetohydromechanik. Glas-Ing. (2002) no. 1, pp. 39–45.

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Contact:
Prof. Dr.-Ing. habil. O. R. Hofmann
Fachbereich Grundlagenwissenschaften
Fachhochschule Jena
Postfach 100314
D-07703 Jena
E-mail: otto.hofmann@fh-jena.de