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Investigation of mass and heat transfer of molten glass in the inductor-crucible

B. Niemann, B. Nacke, M. Kudryash

Abstract

The inductor-crucible is a melting system for the production of glasses with a high efficiency. It is possible to reach temperatures of more than 1700°C without polluting the molten glass. The power consumption is less than for ordinary induction melting systems. In this paper the results of the simulated melting processes are presented. The simulations are done by a numerical simulation tool which calculates the coupled field equations for the electromagnetic, thermal and flow field in a two dimensional geometry.

Introduction

The induction melting of glasses and oxides in cold crucibles for industrial and scientific applications has been well established for several years [1, 2]. This unique method allows the processing of these low conductive materials with high melting points without polluting them. Since an increase in the demand on special materials with outstanding properties was noticed over the last years this fact is of particular importance.

Due to intensive water cooling of the copper crucible a firm layer of the raw material forms around the melt. This so-called skull-layer works like a crucible of the material being melted. It therefore protects the melt against impurities and the crucible against the chemically aggressive melt as well as the high temperatures. Most of the common materials are electrical insulators at ambient temperature. Only by increasing the temperature the electrical conductivity rises strongly. Finally the material couples to the electromagnetic field and melts. Special preheating processes introduce the melting procedure.

Seven years ago the Institute of Electrotechnology (ETP) started to develop and research the inductor-crucible for melting high quality glasses [3, 4]. This alternative induction melting method is principally based on the same effects, but has some important advantages compared to the conventional way. The concept of the inductor-crucible combines the ordinary divided cold crucible and inductor to only one device. The material is melted directly in the inductor. An additional bottom prevents the leakage of liquid melt. Due to the combination of crucible and inductor the electrical losses, occurring when melting with cold crucibles, can be evaded and the power consumption is reduced by 30 percent.

The main field of work for the inductor-crucible is the melting of special glasses which are used as optical fibers. These glasses can only be produced at temperatures in the range of 1500°C or even more. Conventional methods like the use of a platinum crucible are more expensive and cannot offer the same purity. The fibers need to have an absorbability of only 100db/km for the transmission of light with the wavelength of 650nm to 800nm. The absorbability of glasses produced in platinum crucibles increases strongly starting at temperatures of 1300°C due to solute platinum.

The prediction of the behavior of molten glass in the inductor-crucible is very important for example for the design and optimization of a new melting aggregate. Therefore an accurate simulation tool is necessary, because expensive experiments can be avoided in early stages of a development phase. The difficulty of simulation of the inductive melting process of glasses is the strong dependency of each material property on the temperature. Without coupling between the three environments of thermal, electromagnetic and hydrodynamic equations a simulation of the process is not accurate.

1. Simulation tool

In cooperation with the University of Latvia in Riga a simulation tool for the modeling of induction melting processes was developed [5, 6]. This program allows building up axial symmetric models which take into account the electromagnetic, temperature and the flow field. Each of them is coupled and calculated in a transient way. Simplifications like the imprecise reproduction of the slit of the inductor-crucible and the missing input lead have no significant influence on the simulated melting process. All material properties can be included depending on the temperature. The whole melting process from the starting phase to the cooling or casting of the melt can be simulated. This model is used to predict the fusibility and power consumption of new glass types or to optimize the duration of the starting and melting process. The geometry of the required model can be implemented by the user and its only limit is the symmetry to the ordinate. The mesh is generated by dividing each line of the geometry. Fig. 1 shows one example of the mesh of an inductor-crucible model. It is visible that it is possible to compress the mesh density along every line. Especially for problems with high frequency and skin effect the finer meshed regions may offer more accurate results. The input parameters for the time stepping or the process parameters can be changed during the calculation like it is done in practical experiments.

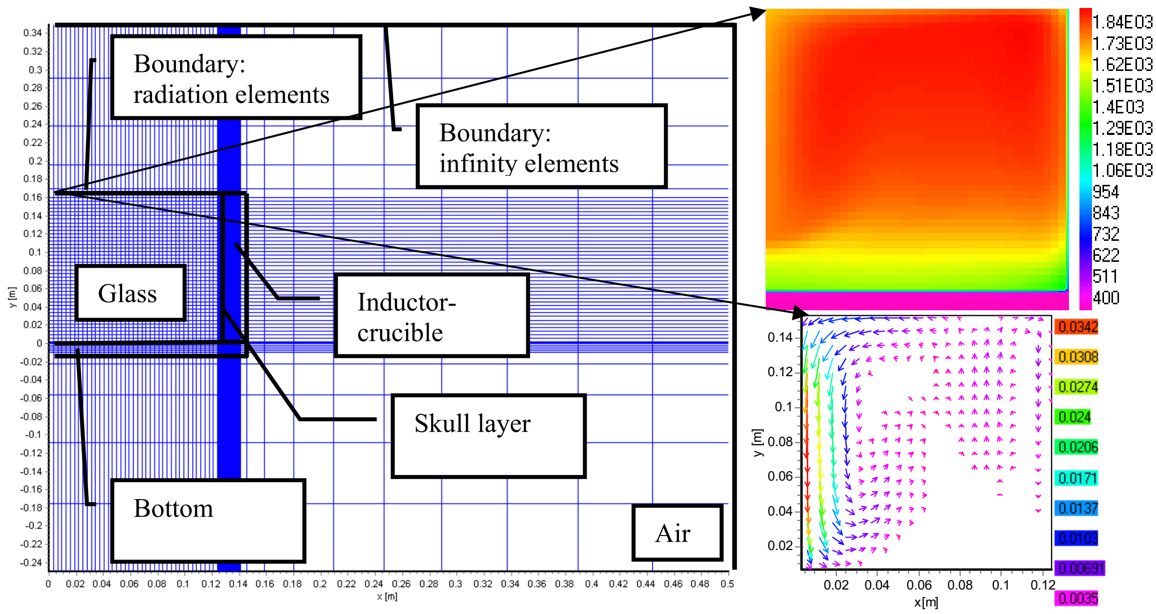


Fig. 1. Example for the mesh of a typical inductor-crucible geometry, temperature and velocity distribution

1.1. Accuracy of the model

The accuracy of a numerical simulation tool is depending on the correct calculation of the equations on the one hand and on the correct material properties on the other hand. For the correctness of the mathematical equations a compromise between the number of elements and the calculation time must be found. With a rather high number of elements the model is more precise but the calculation time is out of a reasonable range. A certain number of elements provides an accuracy that is not possible to increase significantly by the use of more elements. The amount of required elements is depending on the size of geometry which is simulated. For the test of this part it was made a relative easy geometry of a fictive induction melting process of glasses in a ceramic crucible. This work only should show how much numbers of elements are required, when the results do not change anymore. Also the influence of the size of the air box around the fictive furnace and the compression of the meshing along certain lines was tested. Tab. 1 demonstrates that a number of 5000 elements for the application of induction melting of glasses in the current size of the inductor-crucible provides a good accuracy, when the compressed mesh method is used. It is visible that the results do not change significant with a higher quantity of elements. The use of less elements must be assessed critically especially for the velocity.

Tab. 1. Testing results

Number of Elements	Type of mesh	Frequency	Max. velocity	Power in the melt	Max. Temp
1000	ordinary	100 kHz	0,0090 m/s	14,56 kW	1743 K
5000	ordinary		0,0114 m/s	14,71 kW	1758 K
5000	compressed		0,0114 m/s	14,87 kW	1759 K
6900	ordinary		0,0123 m/s	14,79 kW	1761 K
15000	ordinary		0,0122 m/s	15,00 kW	1766 K
1000	ordinary	300 kHz	0,0094 m/s	15,53 kW	1751 K
5000	ordinary		0,0116 m/s	15,34 kW	1764 K
5000	compressed		0,0116 m/s	15,37 kW	1764 K
6900	ordinary		0,0126 m/s	15,35 kW	1767 K
15000	ordinary		0,0123 m/s	15,38 kW	1770 K
15000	compressed		0,0124 m/s	15,38 kW	1770 K

The accuracy of model was verified by a comparing its results with melting experiments. In case of differences adaptations were made. A difficult step was the modeling of the skull layer, because the real material properties of the sintered powder were unknown. Only by an inverse method the thermal conductivity of the skull layer was ascertained. In several simulations with a value between 0.2 and 0.3W/m^{2}K of the thermal conductivity of the used glass were run. The application of a skull layer with real properties provided comparable process data like the voltage and the power consumption. Before the skull layer was included in the simulations the results for the required voltage and power were much higher than known from experiments.

Tab. 2. Comparison of simulation and experiment

	Surface Temperature	Max. Temperature	Voltage	Power losses (Bottom, Crucible)	Radiation
Simulation	1554 °C	1608 °C	595 V	65,3 kW	18,75 kW
Experiment	1555 °C	Not ascertained	584 V	68,38 kW	Not ascertained

Tab. 2 demonstrates the comparison of experiment and simulation. In this case the content of glass was 20 kg and the generator frequency was 100 kHz. It is evident that the measured and simulated parameters have a sufficient accordance. The power losses are the sum of thermal and electrical losses. The temperature distribution in Fig. 2 points at the importance of the numerical simulation. The operator of the experimental process has only the possibility to observe the surface temperature by a pyrometer, because the temperature value and the aggressive melt disallow the direct measurement by thermocouples. In this particular case the final temperature for the experiment was 1550 °C. Only in the simulation or by the solid ingot after the experiment it can be shown that the temperature distribution for this kind of glass is rather inhomogeneous.

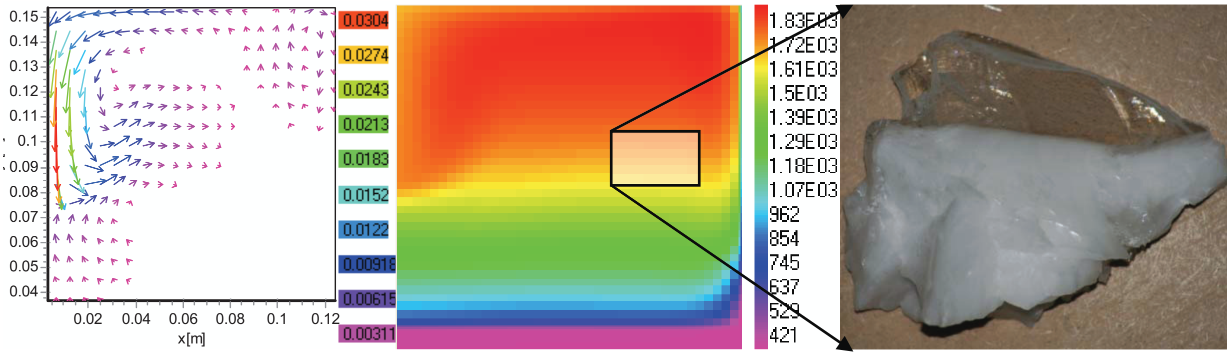


Fig. 2. Temperature and velocity distribution (K and m/s) of the steady state

2. Examples of Simulations

2.1. Glass with a low electrical conductivity

As a first example a simulation of a glass with a rather low electrical conductivity is shown. Before to prepare a practical experiment the simulation must confirm that it is possible to melt this kind of glass in the inductor-crucible. Like it is listed in Tab. 3 the maximum voltage for the used installation cannot exceed 800 V. For this example of low conductive glass the conductivity for the processing temperature is about 25 S/m. Two different frequencies were tested notwithstanding the 600 kHz could not be realised in the installation at the ETP. For the simulation the starting process was simplified to a uniform initial temperature of 1900 K. Nevertheless with both frequencies it was not possible to melt this kind of glass by induction sources in connection with the idealistic starting process.

Tab. 3. Overview of simulation parameters

Frequency	Voltage	Current	Total power	Power in the coil	Power in the melt	Thermal losses	Radiation losses
100 kHz	800 V	6116 A	62.4 kW	23.0 kW	39.2 kW	33.2 kW	21.5 kW
600 kHz	800 V	1025	40,9 kW	1.4 kW	39.4 kW	33.4 kW	21.5 kW

Fig. 3 shows the maximum temperature and the induced power and makes clear that immediately after the end of the starting process at 0 min the temperature and power is decreasing strongly. The reason is to find in the low power which is induced in the melt. The sum of thermal and radiation losses in the according temperature range is much higher than the induced power. For this case the required power exceeds 55 kW for the melt. With the increase of voltage respective current or frequency two possibilities are left but it is not realisable with this installation. In this case a useless experiment could be avoided by the knowledge of the simulation. It can be concluded that a value of the electrical conductivity of a glass should not fall below 30S/m to 50S/m in the range of the according processing temperature. This is depending on the viscosity and so the connected convectional losses the border of the possibility of melting glass in the current inductor-crucible with the frequency limit of 350 kHz.

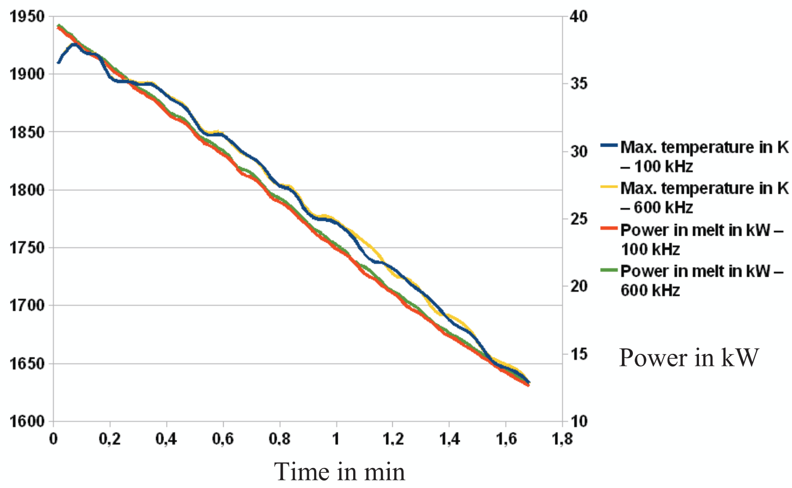


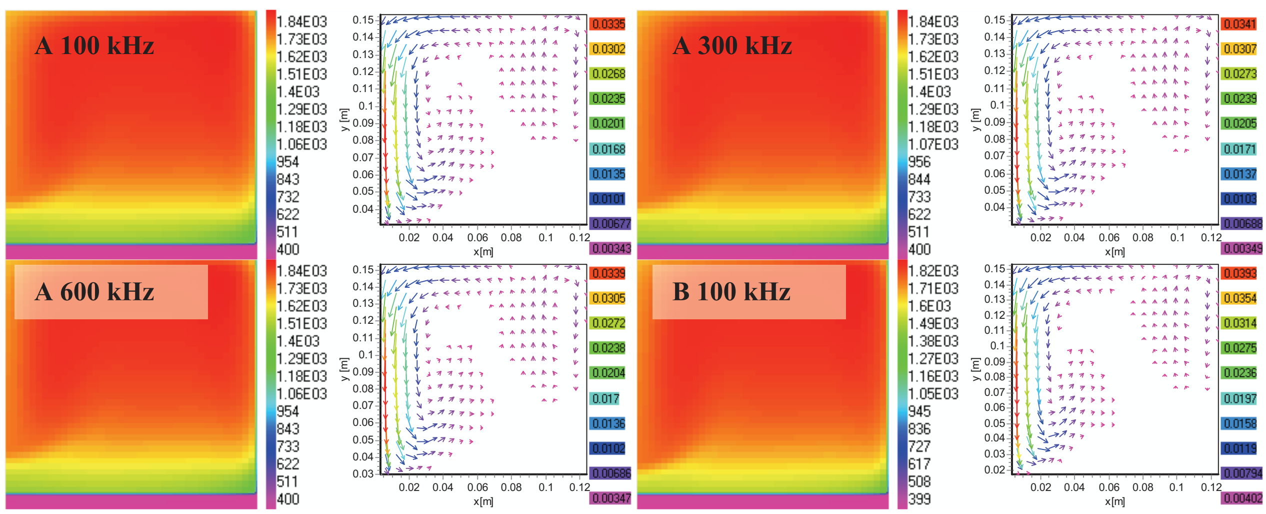
Fig. 3. Trend of the values for power and temperature in the melt

2.2. Heat and mass transfer depending on the frequency

The following investigation was dedicated to carry out the influence of frequency and viscosity on the general movement of the liquid glass. An overview of the simulation matrix and the basic results are in Tab. 4. For two types of glass the melting behaviour was simulated by the use of three frequencies. In Fig. 4 it is visible that the general structure of temperature and velocity distribution is equal. The values for the maximum velocity are increasing about 19 % while the viscosity decreases 50 %. The maximum velocity of each case for the different viscosities is obtained when the heat sources are compacted by the skin effect. It can be concluded that the frequency and the viscosity is not influent for the general movement.

Tab. 4. Important process parameters of the simulated examples

	Frequency	Viscosity at 1400 °C	Power in the melt	Max. Temperature	Max. velocity
glass type A	100 kHz	1,2 kg/m*s	51.2 kW	1895 K	0.0371 m/s
	300 kHz		51.7 kW	1899 K	0.0375 m/s
	600 kHz		51.5 kW	1896 K	0.0374 m/s
glass type B	100 kHz	0,6 kg/m*s	51. 1 kW	1874 K	0.0438 m/s
	300 kHz		51.7 kW	1879 K	0.0446 m/s
	600 kHz		52.5 kW	1886K	0.0459 m/s



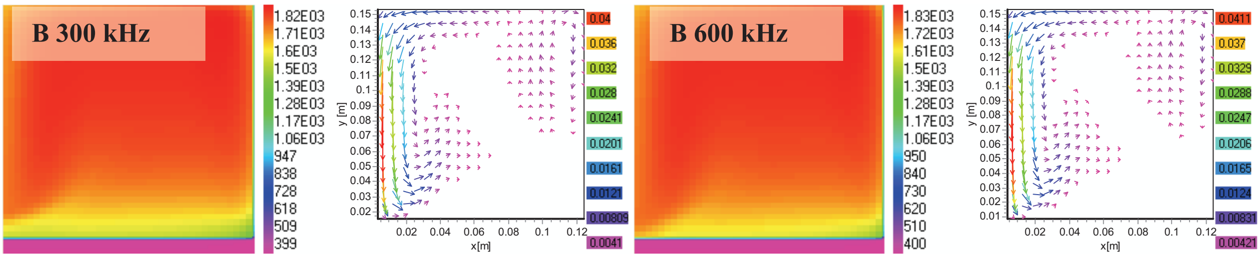


Fig. 4. Temperature in K and velocity distribution in m/s for the different cases of the simulation matrix

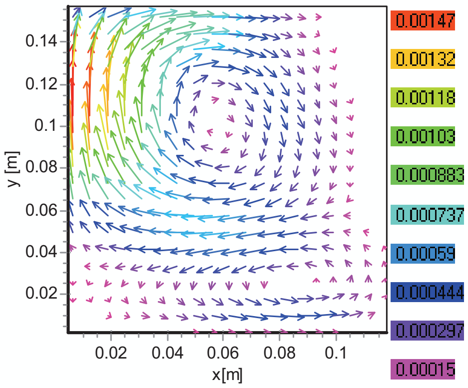


Fig. 5. Velocity distribution without gravity

In Fig. 5 the electromagnetic part of velocity in case of neglected gravity is demonstrated. All other parameters are the same like in case A with 100 kHz. By means of this figure it is detectable that the velocity of liquid glass in the inductor-crucible is mostly driven by convectional forces because the electromagnetic driven velocity has only the tenth part. That makes the movement very stable and predictable for a large range of different glasses with various characteristics and properties.

Conclusions

For the work of the induction melting in inductor-crucibles it is essential to simulate the melting process to avoid high needless costs or even risks of damage. It was shown that the simulation tool was well adapted to the melting process for the inductor-crucible so that predictions of process behavior can be done. For low conductive glasses a border of minimum conductivity for successful melting in the current size of the crucible was carried out by means of simulations. Moreover, the authors could demonstrate that the frequency and the viscosity have only a quantitative influence on the movement of the liquid glass.

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Authors

Dipl.-Ing. Niemann, Benjamin, Prof. Dr.-Ing. Nacke, Bernard, Dipl.-Ing. Kudryash, Maxim
Institute of Electrotechnology (ETP)
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: ewh@ewh.uni-hannover.de