



Proceedings

A Collection of Papers

11th International Seminar
on Furnace Design – Operation & Process Simulation

3rd Glass Forming Simulation Workshop



June 21 – 23, 2011
HOTEL HORAL
VELKE KARLOVICE
CZECH REPUBLIC



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**11th International Seminar on Furnace Design
Operation & Process Simulation**

3rd Glass Forming Simulation Workshop

**June 21 – 23, 2011
Velké Karlovice, Czech Republic**

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NUMERICAL MODELLING OF ANCIENT PRIMARY GLASS FURNACES

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ABSTRACT

The chain of production of glass in the Roman to Byzantine period appears to have consisted of two phases. First, raw glass was made from a silica component fluxed by an alkali component in huge glass furnaces, called tank furnaces. These centres of primary glass production were located close to the sources of alkali and/or silica. For the silica component quartz sand was used, while natron was used for the alkali component. Next, the freshly made primary glass was broken up into chunks and distributed to secondary glass workshops where it was again melted to shape and/or blow it into artefacts.

This paper presents an interdisciplinary study based on a combination of archaeological and archaeometrical research. Excavated primary glass furnaces are used to build a 3D CFD model of the ancient furnaces. Based on CFD calculations we provided further technical insights into the ancient production process such as the duration of the melting process, the amount of energy needed, the evolution of the temperature in the furnaces, etc. We also illustrate that the huge size of the ancient primary glass furnaces could be explained by the existence of economies of scale.

INTRODUCTION

During the last decade archaeology evolved more and more to an interdisciplinary research. This paper is an example and combines archaeological and archaeometrical research to answer archaeological research questions. Therefore a numerical model of excavated primary glass furnaces is built and CFD calculations are carried out.

The first vitreous materials were glazed stones and faience. These were used in the Near East and Egypt from the 4th millennium BC onwards to produce small objects such as beads, scarabs, seals and amulets. In contrast, it was not until about 1500 BC that significant quantities of glass, including glass vessels, began to be produced. However, glass still remained a luxury object at that time. It was only in the Hellenistic-Roman period that the boom of glass production took place. Especially the invention of glass blowing, around the middle of the 1st century BC, resulted in the fact that glass became a more common material. In a very short period of time the technique of glass blowing was spread over the whole Roman Empire. The massive production and consumption of glass continued in the Byzantine and Islamic period [6].

During the Roman and Byzantine period, glass production consisted of two phases. First, raw glass was made from a silica component fluxed by natron. The production of raw glass took place in a relatively limited number of centres located near the sources of the raw materials [3]. The furnaces of these primary glass production centres were huge and the produced raw glass cooled down in the furnaces themselves. Next, the vault of the furnaces was dismantled to extract the big glass slab. This slab was broken up into chunks and distributed to the secondary glass workshops. In these secondary workshops, which were more dispersed, the raw glass was again melted to shape or blow it.

ARCHAEOLOGICAL EVIDENCE OF PRIMARY GLASS FURNACES

The ancient authors Pliny the Elder and Strabo reported that there were three different regions of raw glass production: Syro-Palestine, Egypt and Italy. However, the archaeological record contradicts this last one, as primary glass furnaces were only attested by archaeological excavations in Syro-Palestine [3] and Egypt [8]. At this moment, no primary production centres are found in Italy, though isotopic chemical evidence may be an indication to the production of glass outside the eastern Mediterranean [1]. Therefore, this paper will focus on the two regions where indeed archaeological evidence was found for primary glass production centres and their installations.



Figure 1: Map with the primary glass production centres.

Primary Glass Production in Egypt

During the 1990s archaeological surveys were conducted in Wadi Natrun and in the region of Alexandria to discover sites of primary glass production in Egypt [8]. Three sites were identified in the Wadi Natrun region (Beni Salama, Bir Hooker and Zakik) and two on the shores of Lake Mariout near Alexandria (Taposiris Magna and Marea-Philoxenité).

The Wadi Natrun region is a depression situated between Cairo and Alexandria (see Figure 1) and consists of a number of saline lakes which are presumed to be one of the principal sources of natron in the ancient world. During the year the composition of these evaporitic lakes constantly changes. In winter these lakes contain water, but in summer they vary and in most cases dry out completely and precipitate evaporitic deposits of carbonates, sulphates and chlorides of sodium [9]. The three sites, where traces of primary glass production were recognized, all lie at the end of ways connecting Wadi Natrun with Terenuthis, which was the principal entrepôt and site of shipment of natron over the Nile [7]. Until now, no remains of a secondary workshop in Wadi Natrun have been located and based on the ceramics of the surveys done, it seems that the three centres operated between the 1st and 3rd century AD [7].

The Lake Mariout was in Antiquity a freshwater lake of which the northern shore was separated from the sea by a narrow strip of land of 60 km long (see Figure 1). Its importance for the trade of the whole region is known from Strabo who reports that at Alexandria the harbour on the lake is richer than the maritime harbour (Geography, book XVII, chapter 1, section 7).

Primary Glass Production in Syro-Palestine

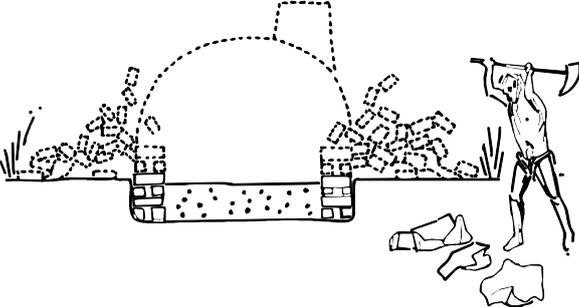
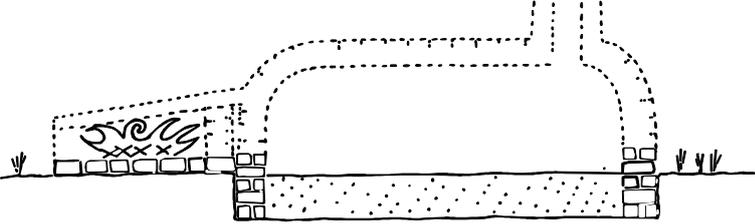
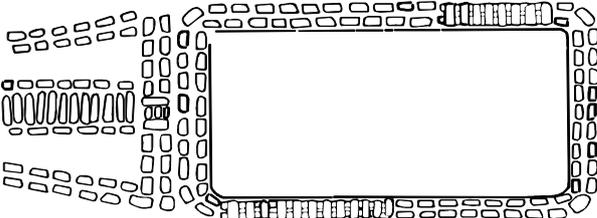
During excavations and surveys from the 1950s onwards three sites were identified in Israel [4]. The site of Apollonia is located on the coast while the sites of Bet Eli'ezer and Bet She'arim are located on few kilometres from the sea (see Figure 1). Until now excavations in Jordan and South Syria have not provided remains of primary glass furnaces. However there are archaeological evidences for numerous secondary glass workshops [2].

CFD MODELLING OF PRIMARY GLASS FURNACES

All excavated primary glass furnaces are of the tank furnace type, i.e. a big melting chamber with a firing chamber at one side and a chimney at the other side (see Figure 2). This causes the arising of a circulation of air and hot combustion gasses from the firing chamber through the melting chamber to the chimney. In this way, the mixture of raw materials is heated in the melting tank.

The 3D model has been built based on the 3D reconstruction of Figure 2 and is shown in Figure 3. The melting chamber has internal dimensions of 2 m by 4 m and the melting tank is

40 cm deep. On top of this melting tank a circular vault with a chimney is assumed. The walls and the vault were constructed of brick and a thickness of 30 cm is supposed. The melting chamber is preceded by a double firing chamber with two separated openings. The vault of these melting chambers is again supposed to be circular.



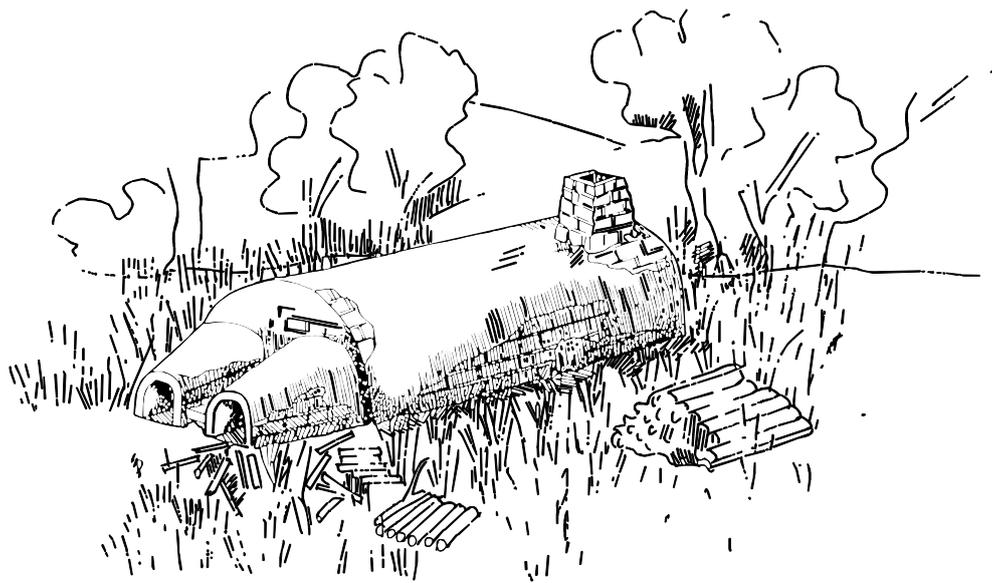


Figure 2: Reconstruction of a furnace at Bet Eli'ezer (Drawing M. Miles) [4].

The type of fuel for the primary glass furnaces remains unknown, but it is likely that different types of wood, charcoal or dung cakes were used. For the simulations combustion of wood is supposed with a conservative estimate of burning 70 kg of wood per hour in each firing chamber. However the total duration of the melting process heavily depends on the amount of energy per time unit put into the firing chambers.

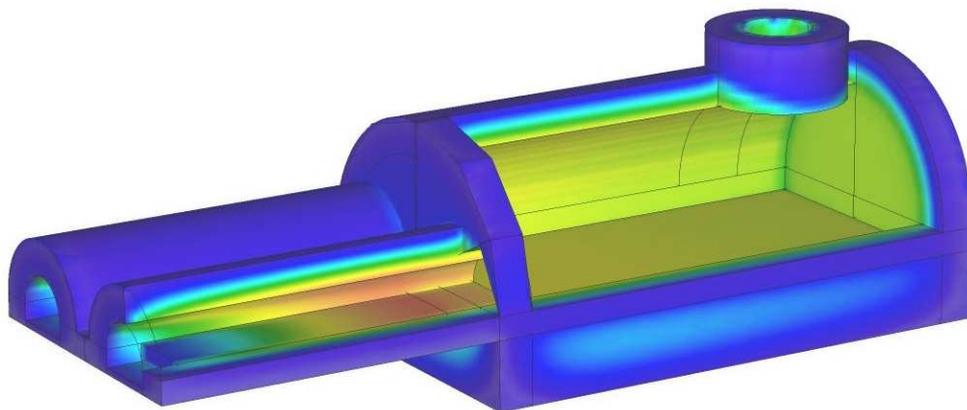


Figure 3: 3D model of a furnace at Bet Eli'ezer.

NUMERICAL SIMULATIONS AND ARCHAEOLOGICAL DISCUSSION

Experiment 1

In a first experiment, stationary calculations are performed whereby the tank of the furnace is filled with 40 cm of glass. In this stationary situation all raw materials are molten and the results are shown in Figure 4. In this figure it is illustrated that the cold gasses are heated in the firing chambers and flow through the melting chamber, where they heat the glass in the tank, and leave the melting chamber via the chimney. Note also that due to the heating a circulation flow arises in the molten glass.

This experiment has illustrated that the temperature is sufficiently high to melt the raw materials and thus the model is representative, but two important questions remain unanswered. Firstly, how the raw materials were melted: the raw materials were simultaneously put all together in the furnaces or were the furnaces charged in consecutive batches of raw materials? Secondly, what could explain the exceptional size of these primary glass furnaces? Therefore a second experiment was carried out.

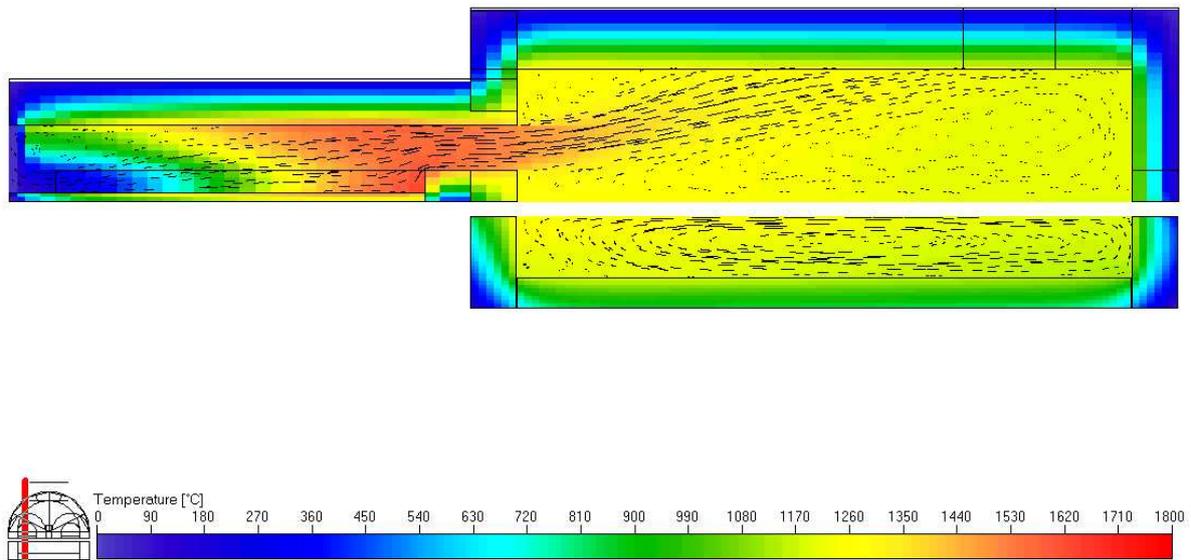


Figure 4: Temperature distribution and flow of both the hot gasses and the molten glass in a section of the furnace.

Experiment 2

In a second experiment, the simulation starts with only 10 cm raw materials in the tank. When these raw materials are melted, the calculated temperatures are taken as initial conditions for the consecutive calculation with 10 cm raw materials above the already 10 cm molten glass. Next the results of these calculations are again used as initial conditions for the consecutive calculations with 10 cm raw materials and 20 cm molten glass, etc. In this case, the gradually charging of the furnace is simulated where each time the heat of the already molten glass is also used to melt the next batch (see Figure 5).

The first results of the non stationary calculations indicate that it is more efficient to charge the furnaces in batches, because the molten glass beneath the raw materials starts flowing. This convection flow in the glass causes that the raw materials also start melting on the bottom side, while the hot gasses still keep on heating on the top side. In this case the raw materials will melt faster and a new batch could be added until the tank is completely filled with molten glass. Further research of the non stationary behaviour is needed for an estimate of time to melt the raw materials batch per batch.

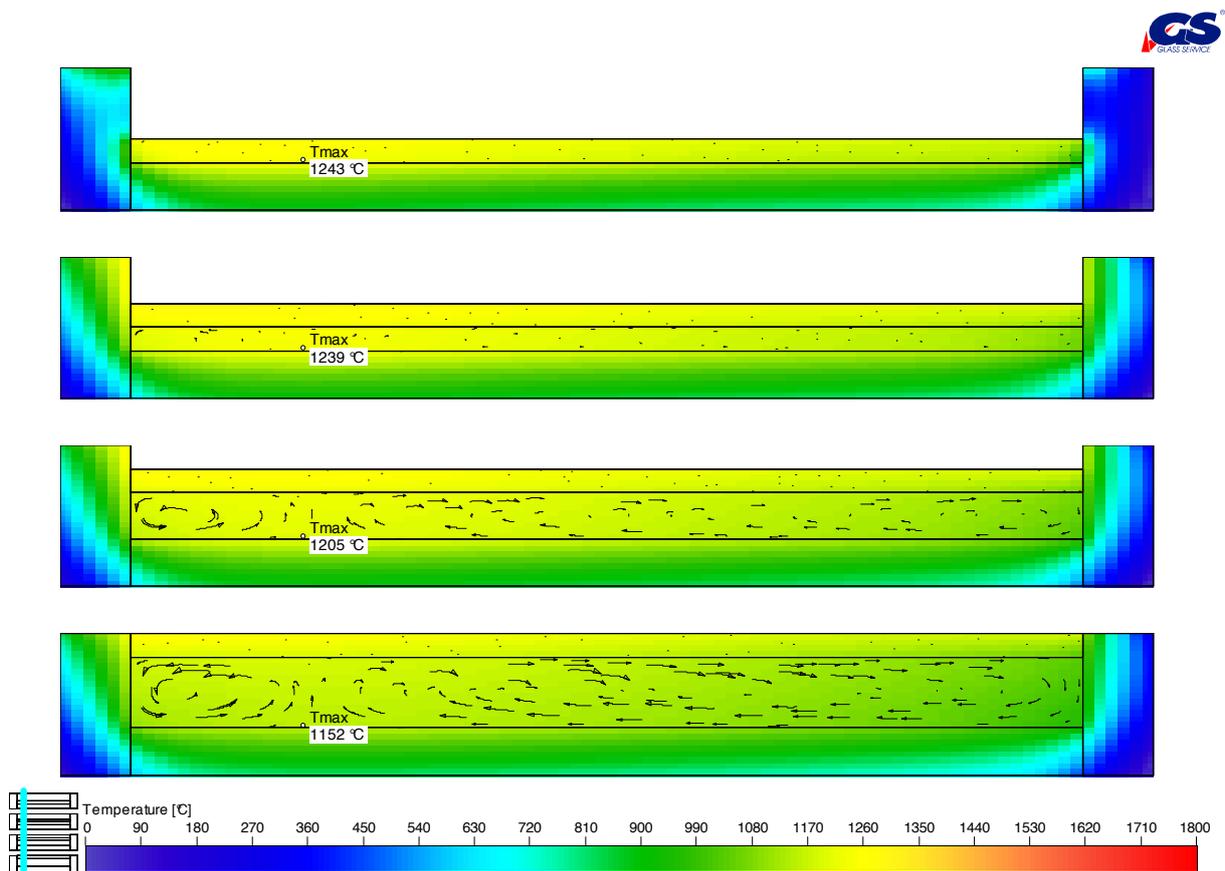


Figure 5: Maximum temperatures at the bottom of the tanks and flow lines in the molten glass in a section of the melting tank at different stages of the melting process with gradually charging of the furnaces.

Discussion

It appears that economies of scale are active at the ancient primary glass production. When a small amount of glass is already molten, it requires remarkably less energy to melt an extra amount of raw materials. This could be a possible explanation of the exceptional size of the primary glass furnaces.

The experiments have also shown that the ancient primary glass production was not only a technical but also a financial tour de force. Firstly, the melting of the raw materials needs a lot of energy due to the high temperatures. When wood combustion is supposed for the heating of the furnaces, the wood needs to be dried and therefore cut many months before its use. Also the construction of the furnaces was intensive labour and took a lot of time. Next the furnaces needed to be heated 24 hours a day and during several days. Also the slow cooling process could take several days. All these big investments were necessary a few months on beforehand which indicates that the big money was involved in the primary glass production.

CONCLUSIONS

The numerical simulations of the CFD model of the primary glass furnaces have illustrated that the huge size of these furnaces could be explained by economies of scale. It is also shown that the melting process is much faster when the raw materials are put in batches, instead off all together in one time, in the furnaces. This can be explained by the fact that in this way the raw materials are at the same time heated from above and from below. Finally, the ancient primary glass production seems to have been not only a technical but also a financial tour de force.

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