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# Modelling possibilities of the medieval bloomery process under laboratory conditions

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## Abstract

Two different models have been developed under laboratory conditions based on the experiences of smelting experiments carried out in bloomery furnaces patterned on some excavated 10-12$^{th}$ century ones. Using Rudabánya iron ore, experiments were conducted in a closed pot and in a small open shaft furnace. During the experiments the air supply, the temperature and the weight of the iron ore and the charcoal were measured. SEM-EDX analyses were performed on bloom pieces obtained from the experiments. The results of the modelling may be correlated with the results of the previous smelting experiments. The model is sufficient for investigating some adequate parameters of the medieval bloomery technology, e.g. the iron yield.

## Introduction

During the recent decades bloomery sites from the Avar age, the time of the Hungarian conquest and the Árpád age have been excavated by industrial archaeologists in the Carpathian basin [1,2]. Archaeometrical and archaeometallurgical investigations have been carried out on archaeometallurgical remains of these bloomery centres [3,4,5,6]. Based on this industrial archaeological and archaeometrical work, smelting experiments have been conducted in bloomery furnaces patterned on excavated types to find the technological parameters of the successful bloomery process. During some of the successful smelting experiments the temperature profile, the gas composition, the sinking speed of the charcoal-iron ore mixture and other parameters were measured [7]. On the basis of the measurements we tried to understand the metallurgical processes of the bloomery furnace [8].

Relying upon the findings of the smelting experiments it can be argued that the technology of medieval iron smelting is very complex. There are several parameters influencing the metallurgical processes of the bloomery furnace. Furthermore, it is hard to provide the same external conditions for the experiments and the human and financial resource demands are also high. Therefore, modelling possibilities of the bloomery process need to be developed under laboratory conditions. Two different models: the open model and the closed model have been developed.

Test-experiments were carried out using iron ore from Rudabánya. The iron ore was examined by X-Ray Fluorescence Spectroscopy (XRF) and X-Ray Diffraction (XRD). The chemical and the mineral composition of the iron ore can be seen in Table 1 and Table 2.

Table 1: XRF analysis results of Rudabánya iron ore

| Mean elements [Wt%] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mg | Al | Si | P | S | Ca | Ti | Cr | Mn | Fe | Cu | Zn |
| 0,220 | 0,250 | 0,470 | 0,149 | 0,006 | 1,030 | 0,016 | 0,021 | 0,250 | 63,100 | 3,19 | 0,121 |

Table 2: XRD analysis results of Rudabánya iron ore

| Mineral phases [Wt%] | | Calculated chem. comp. [Wt%] | |
|---|---|---|---|
| Goet | Hema | $Fe_2O_3$ | $H_2O$ |
| 70 | 25 | 88,57 | 7,10 |

It can be stated that the Rudabánya iron ore has a very high Fe content, its mineral phases are goethite and hematite. The ore has an unusually high Cu content but the Si content is very low comparing the iron ores used in the medieval bloomery technology.
In all the experiments this iron ore was roasted. During the roasting process the iron ore was heated up to 500°C and kept at this temperature for 90mins using a heat treating furnace equipped with silicon carbide rods. After roasting, the mineral composition of the Rudabánya iron ore was almost fully hematite, so it has proved to be an adequate ore for modelling the bloomery process.

**Experiments**

In the closed model a mixture of roasted iron ore and charcoal was heated in a S235 structural steel pot placed into a heat treating furnace equipped with silicon carbide rods. A Pt-PtRh10% thermocouple was inserted from above to measure the temperature directly inside the pot. The air tightness of the pot was secured using clay at the top. The iron ore grain size was between 3-10mm to assure the gas stream between the grains through the iron ore layer. Fig. 1 shows the structure of the closed model.

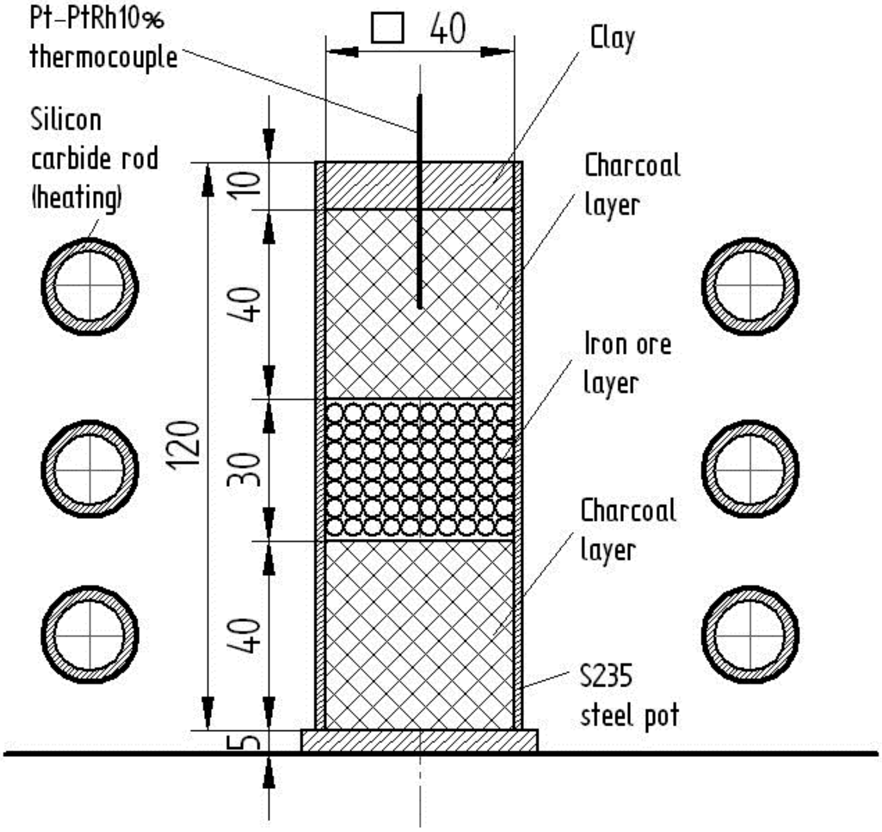



Figure 1: Structure of the closed model

The open model was a 450mm high, 100mm inner diameter shaft furnace. A S235 structural steel tube (twyer) was set in the middle of a prismatic fireclay tube covered with a ceramic fibre thermal insulation blanket. The air supply was assured by a centrifugal ventilator. The volumetric flow rate was regulated by choking the ventilator and it was measured with a single-ball rotameter placed between the ventilator and the twyer. A Pt-PtRh10% thermocouple was inserted 100mm above the twyer to measure the temperature. The amount of charcoal and iron ore charged into the furnace from above was measured as well. Fig. 2 shows the structure of the open model.

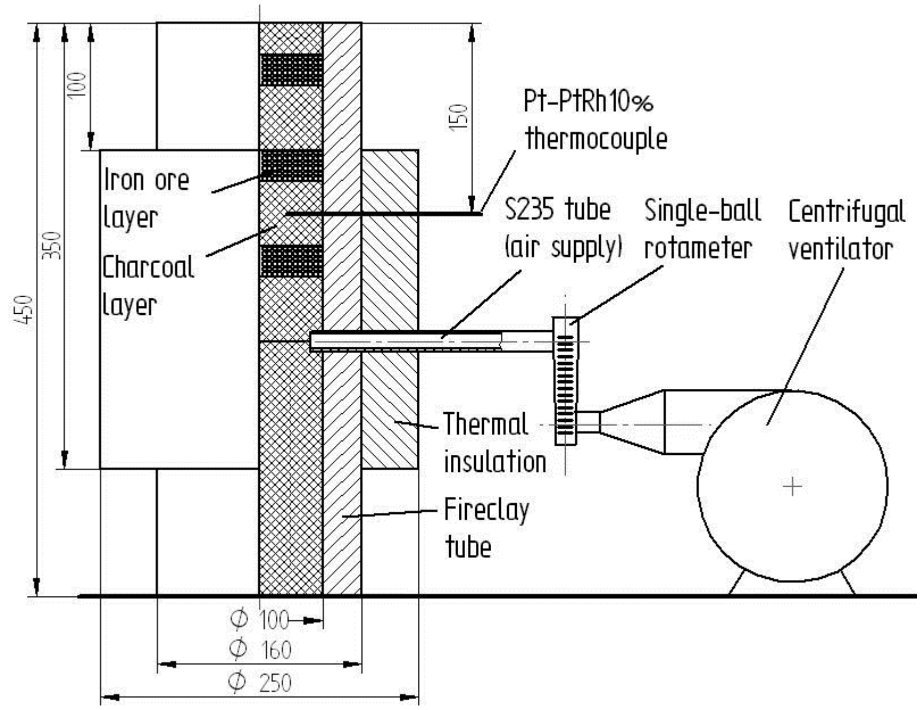



Figure 2: Structure of the open model

**Measurement and analysis results**

There was the following experiment carried out using the closed model. 20grams of roasted iron ore mixed with charcoal was heated continually from room temperature up to 1250°C in 45mins. At the end of the experiment spongy iron pieces (bloom) were reduced from the iron ore. Macroscopic slag was not found.

There were four experiments conducted using the open model with the variation of volumetric flow rate of the air supply at 1l/min, 5l/min, 10l/min and 15l/min. The lower the air supply was, the longer the experiment took. In each case 224grams of roasted iron ore was charged in 5 portions into the preheated and charcoal-filled furnace with 1:0,75 ore:charcoal mass ratio. The grain size of the iron ore was between 3-10mm and the grain size of the charcoal was between 5-15mm. At the end of the experiments spongy metallised iron with more or less slag (bloom) was found under the twyer. The iron was hammered out of the spongy bloom in a cold state and its weight was measured. The weight measurement results and the calculated iron yield are summarised in Table 3. The temperature measurement results can be seen in Fig. 3.

Table 3: Weight measurement results of the experiments with the open and the closed model

| Experiment | $m_{ore}$ [g] | $m_{bloom}$ [g] | $m_{iron}$ [g] | yield [%] |
|---|---|---|---|---|
| open model, 1l/min | 224 | 135 | 41 | 18 |
| open model, 5l/min | 224 | 134 | 59 | 26 |
| open model, 10l/min | 224 | 129 | 112 | 50 |
| open model, 15l/min | 224 | 131 | 71 | 32 |
| closed model | 20 | 14 | 14 | 70 |

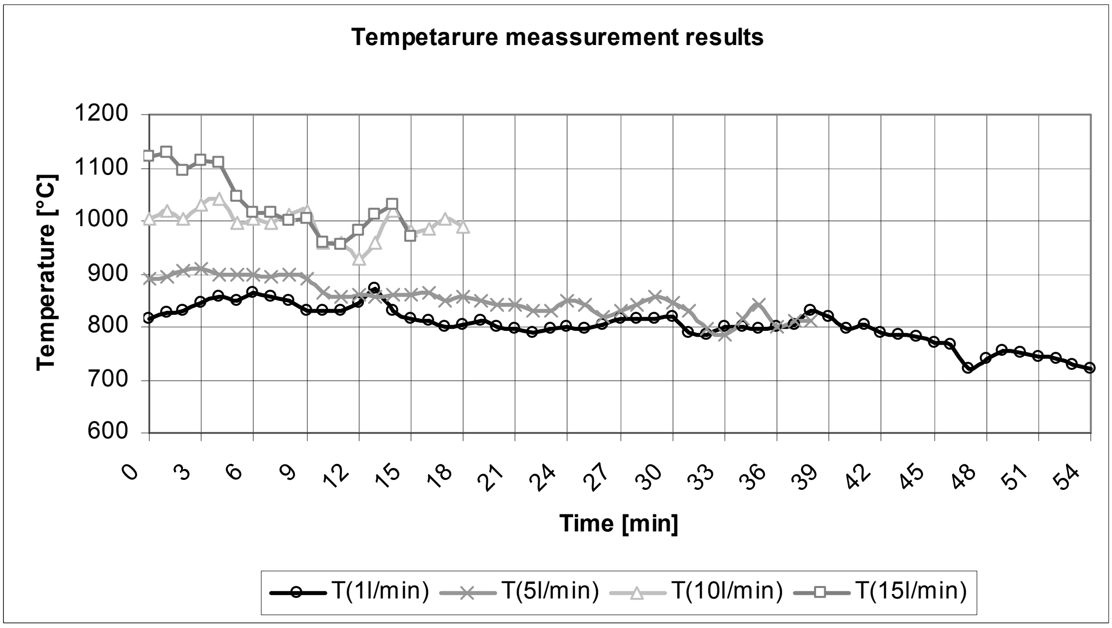
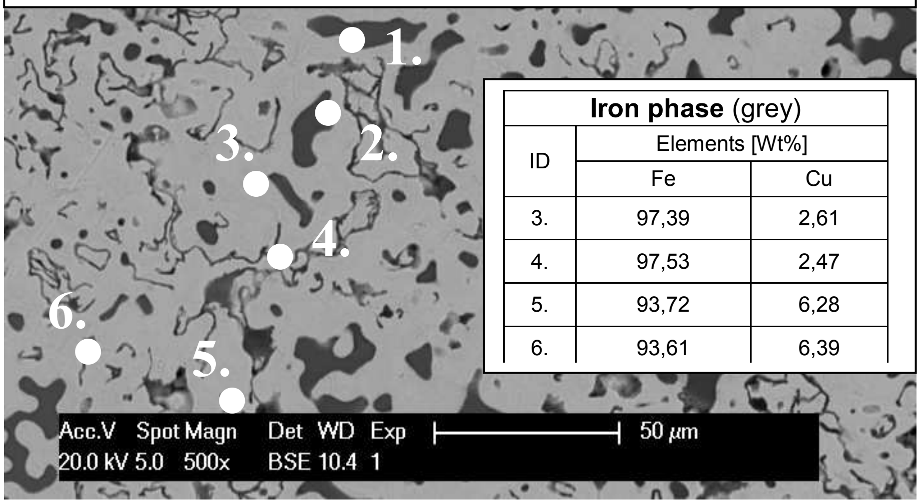



Figure 3: Temperature measurement results of the experiments with the open model

Analyses were carried out on the bloom pieces from the closed experiment and from the 10l/min air supply open experiment using Scanning Electron Microscope and Energy Dispersive X-Ray Spectrometer (SEM-EDX). In both cases the iron phase had low carbon content and the structure was almost completely ferritic. Another analogy was that the high Cu content formed a solid solution of Fe-Cu.

But the slag phase was very different in the two experiments. There was a very small amount of slag phase in the closed model experiment and it had very low iron content. On the other hand, there was more slag phase in the open model experiment and it had very high iron content and a high amount of free wüstit appeared. The SEM-EDX analysis results can be seen in the Fig. 4 and 5.

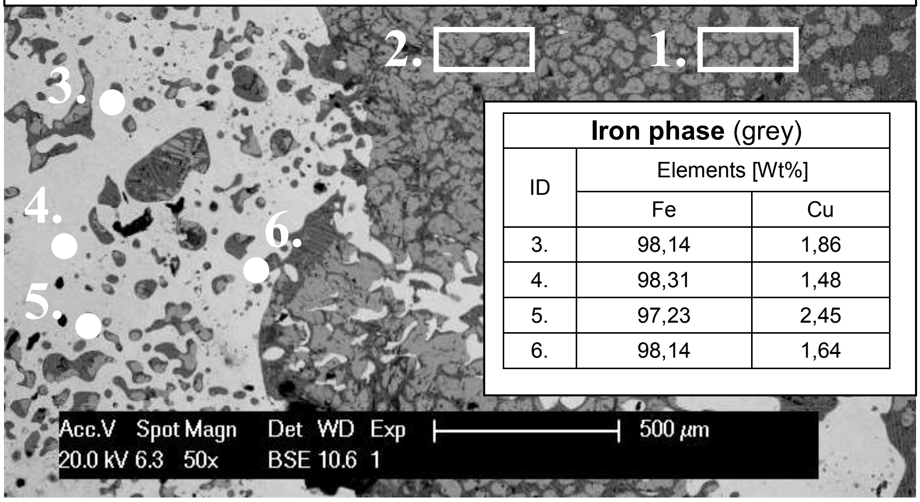
| **Slag phase** (black) | | | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Elements [Wt%] | | | | | | |
| | O | Mg | Al | Si | Ca | Mn | Fe |
| 1. | 24,9 | 6,34 | 6,41 | 38,61 | 3,78 | 11,31 | 6,91 |
| 2. | 23,22 | 3,43 | 6,65 | 34,77 | 5,15 | 19,8 | 4,72 |




| **Iron phase** (grey) | | |
|---|---|---|
| ID | Elements [Wt%] | |
| | Fe | Cu |
| 3. | 97,39 | 2,61 |
| 4. | 97,53 | 2,47 |
| 5. | 93,72 | 6,28 |
| 6. | 93,61 | 6,39 |

Figure 4: SEM-EDX analyses on a bloom piece from the closed model

| Slag phase (black, dark grey) | | | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Elements [Wt%] | | | | | | |
| | O | Mg | Al | Si | Ca | Mn | Fe |
| 1. | 13,98 | 1,18 | 5,14 | 7,64 | 2,36 | 1,06 | 65,93 |
| 2. | 13,23 | 0,96 | 5,43 | 6,12 | 1,64 | 1,02 | 70,21 |




| Iron phase (grey) | | |
|---|---|---|
| ID | Elements [Wt%] | |
| | Fe | Cu |
| 3. | 98,14 | 1,86 |
| 4. | 98,31 | 1,48 |
| 5. | 97,23 | 2,45 |
| 6. | 98,14 | 1,64 |

Figure 5: SEM-EDX analyses on a bloom piece from the 10l/min open model

**Discussion**

The presented experiments are suitable models of the bloomery process since the results converge with those of the smelting experiments (the results should be compared to the results of archaeometrical research as well).

In the closed model, on the basis of SEM-EDX analysis results it can be observed that the slag has almost no iron content, which means that the reduction was almost complete. Therefore, the iron yield has a maximum (equal to the theoretical 70%).

On the other hand, in the open model the reduction is not complete and the iron yield is far from the theoretical. It can be stated that in the open model the iron yield has a maximum in the experiments depending on the air supply. In the previous smelting experiments using Rudabánya iron ore the yield was about 40%. The iron yield in all the experiments is compared in Fig. 7.

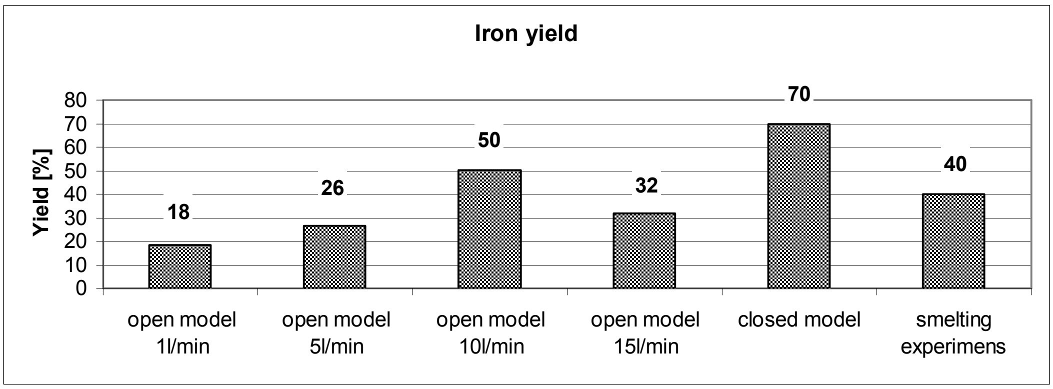



Figure 7: Iron yield in all the experiments

The basic reason for the difference in the iron yield in the closed model and in the open model (and in the smelting experiments) is the difference in the gas atmosphere. In the closed model the Boudouard-balance supervenes as opposed to the open model.

The model could be sufficient in the future not only to investigate the physical-chemical processes and the bloomery technology but for theoretical metallurgical investigations as well.

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