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A natural draught furnace for bronze casting

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ABSTRACT This paper discusses the design and use of natural draught furnaces for non-ferrous casting purposes. A series of experiments was conducted to demonstrate the possibility of using such a furnace without artificial oxygen induction. For comparative reasons the use of bellows was also tested. This paper explores problems of crucible handling, fuel charge and gas flow in the suggested furnace design, and illustrates the thermodynamic principles of such a design and explains why this furnace works.

Introduction

This paper aims to re-evaluate our concept of reconstructing the metallurgical production process of bronze casting, or rather the preceding step of bronze melting. The use of bellows seems all too often implicitly accepted and this experimental case study on low shaft, natural draught furnaces[1] offers an alternative way for interpreting features related to metal casting traces at archaeological sites. Natural draught furnaces are not to be confused with wind-powered furnaces, where wind above the furnace is the main factor for producing sufficient updraught (e.g. Juleff 1996; Tabor *et al*. 2005).

The use of natural draught furnaces for metallurgical processes has been noted and published for several decades, mostly in relation to smelting processes (e.g. Percy 1864; Cline 1937; Tylecote 1987). Despite this and the fact that these furnaces are still in use in present-day bronze art foundries, they seem not to be recognised as viable alternatives for the production of non-ferrous metal artefacts in antiquity. In the archaeological literature they are typically mentioned in connection with extractive metallurgy (e.g. Rehder 1987), but never with the casting of bronze. This is all the more intriguing as for the high-medieval period Theophilus Presbyter reports the use of a natural draught furnace for the melting and production of brass (Hawthorne and Smith 1979; Brepohl 1999) and in the Renaissance, Benvenuto Cellini (Brepohl 2005) reports the use of natural draught for casting furnaces.

Why it is believed that furnaces need forced air supply

The bias in favour of bellows and tuyères,[2] i.e. forced draught furnaces, seems deeply rooted in archaeologists' perception of high temperature processes and might have misled our interpretations, or at least distorted the image of metal foundry in antiquity. The lack of clear-cut archaeological evidence for the design of bronze casting furnaces certainly constrains our interpretation. Tuyères are frequent, but their number bears no relation to the amount of archaeological bronze objects – it would be expected that a highly fired or vitrified artefact such as a tuyère should survive in the archaeological record. In contrast, bellows – probably manufactured from organic materials – would not be expected to survive and are accordingly very rare in the archaeological record. We notice that there are neither enough tuyères nor bellows in the record to explain why high temperature processes are usually reconstructed in a way that assumes their presence. As a rule, the archaeological record provides furnace bases at best, whereas the once existing superstructure is almost always lost and the reconstruction has to be based on a set of assumptions.

The following aspects may have biased these assumptions: first, the tradition in the metal crafts, maintained by present-day craftsmen. However, only a few archaeologists have had formal training as craftsmen, and thus evaluating information retrieved from such a source might prove difficult and lead to misinterpretations. Secondly, historical sources such as Georgius Agricola (2003), Vannoccio Biringuccio (Smith and Gnudi 1990) and Lazarus Ercker (1598) report the use of bellows and emphasise their usage. Further back in human history, Roman and Greek depictions of metalworking scenes exhibiting the use of bellows can be found. Even some Egyptian wall paintings, for example those from Rekh-Mi-Re (Davies 1973), Mereruka (Duell 1938) or Meir (Blackman 1914), give evidence for the use of bellows in high temperature processes, including the casting of metals. Archaeologically, Davey (1979) has shown the existence of pot bellows for the Near East, at least from the 2nd millennium BC onwards, which tallies well with the above-mentioned pictorial evidence in Egyptian tombs. Looking closely at this evidence it can be seen that there is one instance from Egypt and one from the Greek world in which casting of metals is depicted (Oddy and Swaddling 1985; Weisgerber and Roden 1986; Tylecote 1987; Pusch 1990, 1994). In Roman times, depictions of bellows are associated predominantly with blacksmithing (Weisgerber and Roden 1985). It might not yet be fully appreciated in the archaeological world that there is a clear distinction between foundry work and metal forging, and subconsciously the terms 'metal-founder' and 'metalsmith' might have been used synonymously. It can be argued that this ambiguity might well be partly responsible for the bias in favour of forced draught furnaces.

It is generally believed that, in Europe, separate chimneys have been in existence only from the 12th century onwards; this obscures the fact that even an ordinary campfire produces an updraught above the fire, and in doing so creates a low pressure zone at the base of the fire. The difference between ambient air pressure and the lower pressure zone at the campfire's base will result in an air flow from the higher pressure zone towards the lower pressure zone; thus, air is transported towards the fire and supplies it with oxygen. In summary, there is ample reason to assume that natural draught furnaces may have played a much larger role in metal casting than hitherto acknowledged.

Aims and methods

A series of experiments with low shaft furnaces was conducted to evaluate the potential of natural draught shaft furnaces for melting, superheating and casting non-ferrous metal. The experiments draw upon more than 10 years of professional experience in bronze casting, both with modern and reconstructed casting tools and equipment. Questions regarding the functionality and practicability of this design are:

- Will the furnace work at all?
- What temperature will the furnace reach?
- Will the temperature be consistent enough to melt and superheat the metal?
- How does charging affect the furnace's performance?
- Does fuel lump size have an effect on performance?
- Is the handling of crucibles without modern steel or iron tongs possible?
- How much time does the furnace need to dry? Can it be used immediately?
- Is there a difference in performance between a cold furnace and a continuously used hot furnace?
- Is this mode of furnace operation practicable for a production environment?
- How much investment of labour and material does a furnace like this require? Is it valuable? Does it need sheltering?
- Can an experiment answer these questions?

Experimental set-up

Furnace

The furnace type that was tested is a simple shaft furnace circular in plan and slightly conical in side view (Figs 1 and 9). The external diameter is 42 cm at the bottom, 27 cm at the top and the height is 45 cm. The inner diameter, which is 20 cm at the bottom and 15 cm at the top, is of importance. The bottom of the furnace is slightly bowl-shaped. At ground level there are three 10 × 6 cm air inlets. The building material is clay with 60–70% quartz temper, and wall thickness varies from 11 cm at the bottom to 6 cm at the top. The furnace was built entirely from fresh clay and dried within the day by firing it with wood and charcoal for several hours preceding the experiment.

The furnace works with a crucible placed in the charcoal charge, whereby the bottom of the crucible is approximately 6 cm above ground level. This ensures that the crucible receives the maximum heat during charcoal combustion.

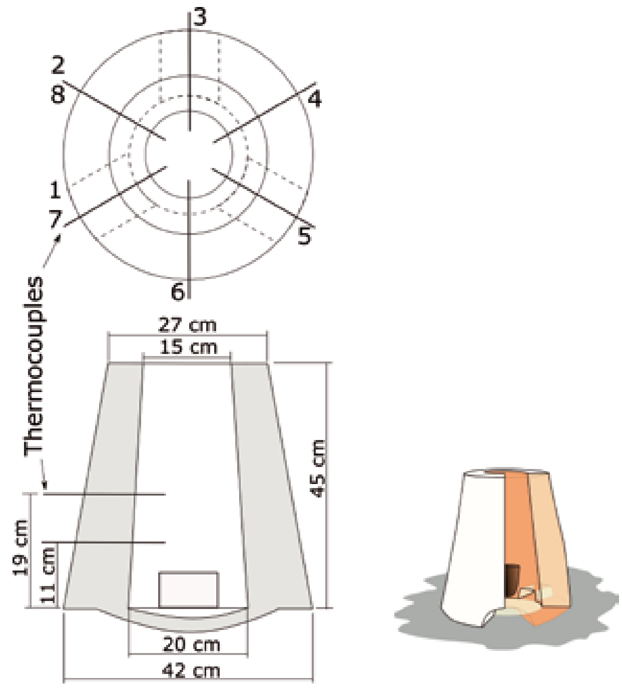

Figure 1 Plan and side view of the experimental shaft furnace. The numbers 1–8 denominate the two principal sets of positions of the thermocouples; the side view shows the thermocouples' elevation above ground.

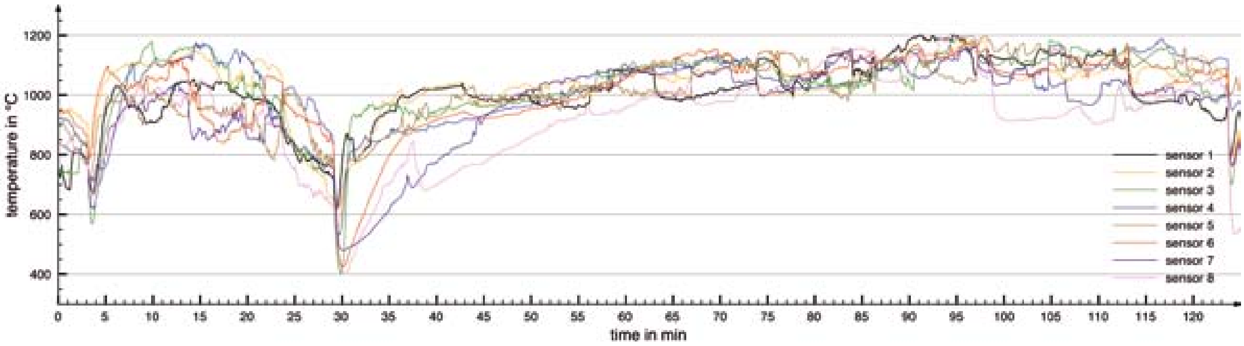

Figure 2 Plot 1: an episode with the shaft fully charged with charcoal. Note that the y-axis starts only at 300 °C.

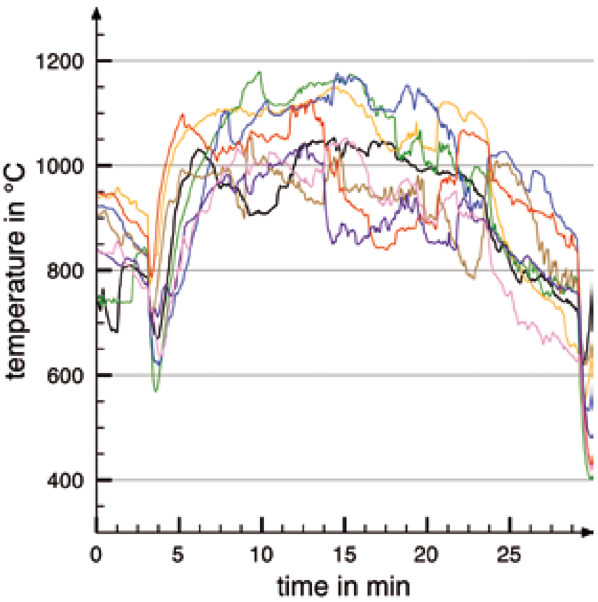

Figure 3 Plot 2: shaft half-filled with charcoal. Note that the y-axis only starts at 300 °C.

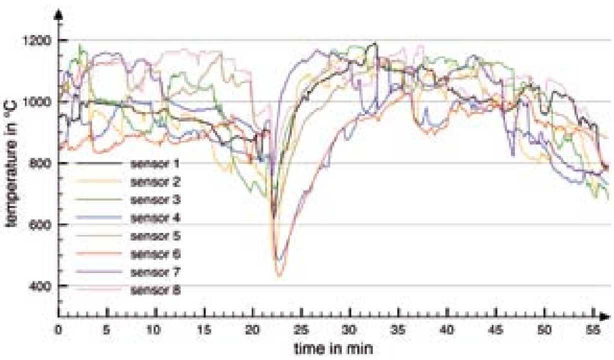

Figure 4 Plot 3: two consecutive cycles with the shaft half-filled. Note that the y-axis only starts at 300 °C.

The hottest zone in the furnace is easily identified by the yellow-orange colour of the embers; additionally, the embers will exhibit white edges if they burn hot. The crucible itself is filled with metal and completely immersed in charcoal. No lid or cover for the crucible is necessary – the charcoal on the metal prevents oxidation while producing additional heat from the top.

Temperature measurements

Temperatures within the furnace were taken with type N thermocouples and data logging equipment, which could handle up to eight thermocouples simultaneously. Previous experience led to the observation that the highest temperatures are to be expected immediately above the air inlets. Therefore, two distinct sets of positions for thermocouples were chosen: positions 1, 3, 5 and 7 above air inlets and positions 2, 4, 6 and 8 between air inlets. The thermocouples protruded 5 cm into the furnace. Six thermocouples were placed 11 cm above ground and two others 20 cm above ground (Fig. 8).

Bellows were available for the experiments and their impact on the melting process was monitored in one single cycle. The bellow nozzle[3] did not protrude into the furnace. Only one air inlet was supplied with a forced draught.

The charcoal used for the experiments was obtained from local char-burners and the main wood species used were oak and beech.

Results

Plot 1 in Figure 2 represents temperature data of a furnace cycle with a shaft completely filled with charcoal. Figure 3 represents one cycle with the shaft half-filled and Figure 4 shows the temperature in two consecutive cycles with the shaft half-filled. The drop in temperature in the plots represents recharging events with fresh charcoal. It can clearly be seen that the temperature decreases by 500 °C after each charging event. This loss of temperature also affects the metal in the crucible and in doing so prolongs the time that is required to liquefy the metal.

A maximum temperature of just over 1200 °C was reached, however the average operating temperature of a continuously used furnace was found to range between 1000 °C and 1200 °C. The temperature was maintained sufficiently long to melt a 90/10 tin bronze with a liquidus temperature of 990 °C (Shim *et al*. 1996). The time the high temperature range lasted depended on the amount of charcoal – from 15 minutes with a half-filled shaft (Figs 3 and 4) to up to an hour with a completely filled shaft (see Fig. 2). The degree of variability in the operating temperature is less if the furnace is filled completely with charcoal and the melting of bronze was accomplished within this cycle. However, it was found that melting and superheating the metal was achieved considerably faster with two cycles of charging the shaft halfway.

The wet furnace immediately after building did not reach the necessary temperature. No measurements were taken, but the bronze in the crucible remained solid and even after several hours of firing it had only a dark red glow colour which attests a temperature of approximately 700 °C.

The performance of the furnace increased with continuous use. A cold but dry furnace did work to melt the bronze, but took considerably longer and consumed a much larger amount of charcoal than a hot furnace, which was in continuous use. In a cold furnace, the melting of bronze took 60–75 minutes whereas it only needed 20–25 minutes in a hot furnace.

It was found that the charcoal lump size plays a major role in the melting process. During combustion the charcoal fragmented into numerous smaller lumps. Once the gross charcoal lump size is below 15 mm in the area of the air inlets, the air flow within the furnace is impeded to such an extent that temperatures above 1000 °C are not achievable.

Because the crucible moves downwards (and away from the hottest zone in the furnace) in the shaft as the combustion of the charcoal progresses, its position has to be monitored and corrected regularly. The crucible was handled with tongs made from green wood, which is more difficult than using steel tongs, but nevertheless it was possible and casting could proceed without any noticeable delay (Fig. 5). The tongs also proved sufficient for the repeated positional corrections of the crucible during melting. Because wood has a lower thermal conductivity than metal, wooden tongs kept heat loss to a bare minimum at the most crucial part of the casting sequence, i.e. retrieving the crucibles and casting the metal – metal tongs immediately cool down the crucible (as evidenced by the crucible's change of colour) whereas the crucibles retrieved with wooden tongs maintained their temperature.

Figure 5 Casting with wooden tongs.

During experimentation, a simple and effective heat protection for hands was also found: clay slips applied on hands and arms protect the skin adequately when pulling the crucible and pouring metal into the moulds, even though a considerable amount of time is spent above the shaft of the furnace.

Observations on the use of bellows

During the experimentation with bellows, the temperature in the furnace rose immediately above the range of the thermocouples and they had to be withdrawn from the furnace. Simultaneously, charcoal consumption increased noticeably. It appeared, however, that the melting speed did not increase significantly, despite the increased oxygen supply: the charcoal burned hotter, but also much faster, and the necessity to recharge the furnace with charcoal more often seemed to counterbalance the effect of the hotter furnace. This touches on a general problem with melting metal in solid fuel furnaces, i.e. that the operator has to constantly evaluate the temperature versus the availability of fuel. In this respect it was found that the use of bellows enabled the operator to achieve better furnace temperature control. Towards the end of a charcoal cycle, instead of recharging it with charcoal, there is the opportunity to raise the temperature very quickly with the use of bellows and use this additional energy to superheat the metal.

In summary, the furnace operated in a very satisfactory fashion and several kilograms of bronze were cast into shape during the experiments.

Discussion

If we strive to reconstruct how metal is molten in a furnace, we need to understand the physical processes that govern how metal melts, what happens during combustion of a fuel, and the behaviour of gas and flue in our furnace. With regard to the melting of metal we have to consider the following three physical properties of matter: (1) the melting temperature, (2) the specific heat capacity and (3) the standard enthalpy of fusion.

Table 1 Physical properties of metals.

	Melting temperature in °C	Specific heat capacity (c_p) in kJ kg^{-1}K^{-1}	Standard enthalpy of fusion ($\Delta_{fus}H$) in kJ kg–1
Copper	1083	0.385	205
Tin bronze	1020	0.38	190
Silver	962	0.232	105
Brass 63/37	920	0.377	166
Gold	1064	0.129	63
Lead	327	0.129	25

Melting temperature is the temperature at which a material is fully liquefied, also referred to as the liquidus temperature (see Table 1 for melting temperatures of various metals). However, a heat source that exceeds the melting temperature of a metal does not necessarily melt it. Consider the following: a candle flame has a temperature of 1300 °C but it cannot melt bronze. This is why we need an additional concept to that of temperature: energy. Energy and temperature together can explain the physical reactions during the melting of metals. The specific heat capacity (c_p) is a measure of how many units of energy are necessary to increase the temperature of 1 kg of matter by 1 °C (or 1 K = Kelvin). In order to heat 1 kg of bronze from room temperature to its melting temperature, we can calculate the energy Q with the equation:

$$Q = m_{bronze} * c_p * \Delta t$$

where:

c_p specific heat capacity for 90/10 tin bronze: 0.38 kJ kg^{-1} (see Table 1)

Melting temperature 90/10 bronze: 990 °C

m_{bronze} mass of bronze 1 kg

Δt = 990 °C–25 °C = 965 °C = 965 K

$$Q = 1\ kg * 0.38\ kJ\ kg^{-1}\ K^{-1} * 965\ K = 367\ kJ$$

Although the metal is at melting temperature, after this amount of energy is applied it is still in a solid state due to the microstructure of metal – because the metal is held together in a crystal lattice, extra energy has to be applied to dissolve the metallic bond. This amount of energy is called the standard enthalpy of fusion ($\Delta_{fus}H$) and the amount of energy Q_{fus} required can be calculated as follows:

$$Q_{fus} = m_{bronze} * \Delta_{fus}H$$

$$Q_{fus} = 1\ kg * 190\ kJ\ kg^{-1} = 190\ kJ$$

One kilogram of bronze needs 190 kJ to dissolve its crystal lattice. The total amount of energy Q_{melt} is:

$$Q_{melt} = Q + Q_{fus} = 367\ kJ + 190\ kJ = 557\ kJ$$

But in order to be able to retrieve the crucible from the furnace and pour the metal into the mould, its temperature needs to be raised by at least another 150 °C – this is called superheating. Again, the specific heat capacity is used to calculate the energy Q_{super} required to superheat the metal:

$$Q_{super} = 1\ kg * 150\ K * 0.38\ kJ\ kg^{-1}\ K^{-1} = 57\ kJ$$

$$Q_{tot} = Q_{melt} + Q_{super} = 567\ kJ + 57\ kJ = 624\ kJ$$

The additional energy requirement is 57 kJ. Altogether 624 kJ is required to melt and superheat 1 kg of tin bronze.

Let us now examine the heating value of charcoal to understand how much energy it provides. Because charcoal is produced under non-standardised conditions, it is difficult to quantify its heating value. This is further complicated by the fact that wood species can vary widely in their chemical composition and their calorific values. For the purposes of this paper, an average value for the higher heating value (HHV) of charcoal is assumed to be 28 MJ kg^{-1}, taken from the *Kirk-Othmer Encyclopedia of Chemical Technology* (Durbak *et al.* 1999). However, the amount of energy that can be used in our scenario is the lower heating value (LHV), which takes the heat loss of water evaporation (i.e. water that is present in the fuel) into account. As a rough approximation, this value is 90–95% of the HHV (Rehder 2000: 35), so that a conservative value of 25 MJ kg^{-1} is used. This means that 1 kg of charcoal generates 25 MJ of energy in the form of heat during combustion.

Although this value seems high at first glance, providing 40 times the energy that is required to melt 1 kg of bronze, in practice 1 kg of charcoal is not necessarily enough fuel to melt the bronze. The main obstacle to overcome is that of heat loss. In order to melt the metal successfully, the sum of the heat losses should be smaller than the lower heating value plus the energy required for the melting of the metal. Heat losses include losses through heat conduction, i.e. heat convection and heat radiation (Rehder 2000: 10); in other words, the heating of the furnace wall, the heating of the crucible, the heating of ambient air around the furnace and of course the evaporation of water, which is abundantly present in all the structural elements built from clay. This is the reason why a wet furnace does not work properly. In order to evaporate water, tremendous amounts of energy are required. The most substantial 'heat loss', however, is caused by the large upper diameter of the shaft through which the flue escapes and which creates the updraught. Looking at the gas flow in more detail, the thermodynamic principles at work in the shaft furnace are (1) Bernoulli's theorem and (2) the hydrodynamic paradox. These two phenomena can be used to explain how and why the air supply of this furnace works.

Bernoulli's theorem

In fluid flow an increase in velocity occurs simultaneously with decrease in pressure. Bernoulli's theorem can be used to explain why any fire is sufficiently supplied with oxygen. In thermodynamics, the term fluid is applied to gases and liquids alike. We are concerned with the flue of the furnace. The flue consists mainly of carbon monoxide and by-products of the furnace operation, but also other components of air, such as nitrogen, which are of no concern here. Importantly, the gas directly above the charcoal bed is more than 1000 °C hotter than the air outside the furnace, which means that the velocity of its molecules is increased notably. This increase in velocity results in a decrease of pressure above and around the furnace, the updraught. This lack of pressure is immediately counterbalanced by the atmospheric pressure, which pushes cold air towards the low pressure zone and supplies the furnace with air. This air is used for combustion and thereby heated, maintaining the low pressure zone above and around the furnace as long as it is hot (see Fig. 6).

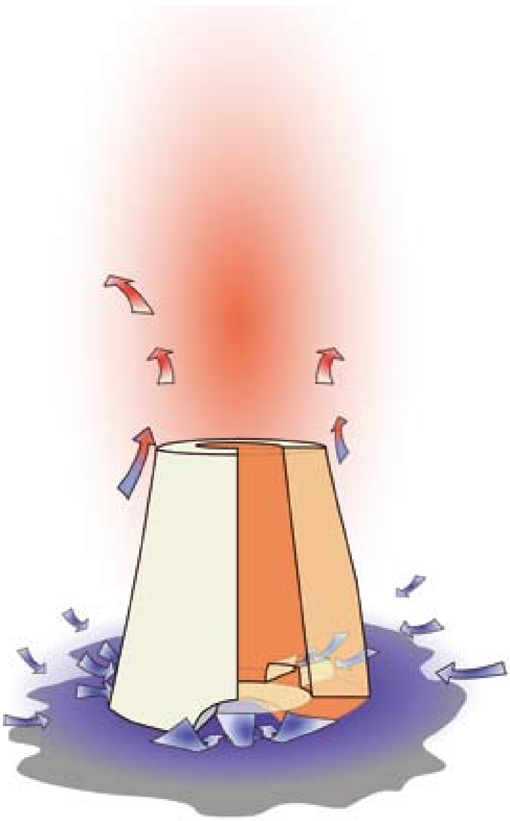

Figure 6 Bernoulli's theorem: hot air rises, leaving a zone of lower pressure at air inlets. Atmospheric pressure compensates the lower pressure zone by pushing air into the inlets.

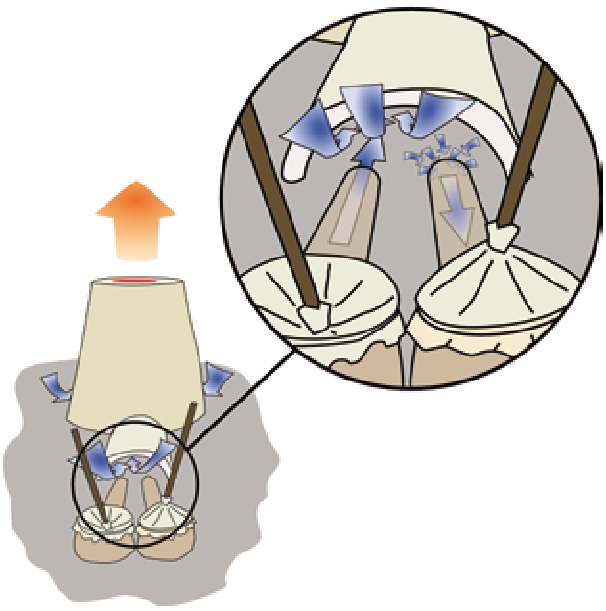

Figure 7 The hydrodynamic paradox: objects bordering streaming fluids are pulled towards them and not pushed away.

The hydrodynamic paradox

Objects bordering a streaming fluid are pulled towards it and not pushed away (see Fig. 7). This is especially important for the use of pot bellows without valves. Because these bellows release the air via the same nozzles through which they aspirate, the bellows must not protrude into the furnace in case they suck in hot fumes or embers, alighting the bellows. Nevertheless, such bellows (see Fig. 10) were and are used successfully for metallurgical processes. Because we are able to push an air column for a few centimetres, it is possible to induce air into a furnace through air inlets. Additionally, ambient air is swept along the air column into the furnace, inducing more air into the furnace than that supplied by the bellows. Fortunately it is impossible to draw a column of air into the bellows – as soon as the leather skin is pulled upwards, an under pressure is produced and the atmospheric pressure pushes air into the bellow.

The value of a furnace

Obviously it is very difficult to assign values to material objects of past societies, especially if they are to be understood solely through their material remains. Nevertheless, an understanding of the value of such a device can be facilitated by examining the investment of labour in order to produce such a structure. 'Value' refers to the willingness of protecting this installation against atmospheric conditions or other forces that might lead to its destruction.

The tempering and kneading of the clay took about an hour. The time to build the furnace was approximately 40 minutes. It seems unlikely that a shelter for furnaces of such a design would have been built if we compare the amount of labour and raw material procurement to build even the simplest shelter with the labour that went into the building of the furnace.

One of the furnaces was left unprotected throughout the winter on the experimentation field in London. The structure proved comparatively resilient against weathering and could be used in the spring without requiring major repairs. There is no doubt however that rain in combination with frost would have led to its destruction within the year, with hardly any trace being left in the archaeological record apart from a few droplets of metal.

Conclusions

The experiments clearly demonstrated that the use of natural draught is sufficient to melt and superheat a tin bronze with 10% tin content. After continuous use of several hours the furnace maintained a temperature above 1100 °C for periods of up to 15 minutes with the shaft half-stacked and up to an hour with the shaft full of charcoal. A maximum temperature of 1208 °C was reached. At each charging episode the temperature decreased by approximately 500 °C for a

Figure 8 Experimental set-up in one of the experiments.

Figure 9 Furnace after one week of continuous operation. Cracks may easily be repaired with fresh clay. Because of the conical shape, the furnace is unlikely to break apart.

Figure 10 Recent wooden pot bellows.

period of 7–15 minutes, depending on the amount of charcoal charge in the shaft. It was observed that charcoal lump sizes below 15 mm impede the gas flow to such an extent that temperatures above 1000 °C are not achievable. The use of wooden tongs for managing the crucible in the furnace as well as handling the hot crucible proved very successful, and helped to minimise heat losses of the melt due to lower thermal conductivity of wood compared to metal.

In summary, it can be stated that low shaft natural draught furnaces are easy to build and can be used very successfully for the production of the majority of bronze artefacts of a mass ranging from 1 to 2 kg.

Notes

1. A furnace is a structure used for high temperature processes such as casting, glassmaking or smelting.
2. Tuyères are discrete implements, and usually not structural features of a furnace. They are generally more or less conical tubes of refractory material and taper towards the end that points (and may protrude) into the furnace. It is their function to induce air into the furnace.
3. The definition of nozzles is somewhat imprecise: on the one hand, they are often seen used in conjunction with blowpipes in order to prevent the tip of the organic blowpipe from alighting, but they are smaller in dimensions than tuyères. On the other hand, nozzles are structural parts of bellows where the air leaves the bellows (e.g. Davey 1979), and because of this they are sometimes confused with tuyères.

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