Smelting Science

4. Supplying Air to Smelters

Supplying Air

There are essentially four ways of getting air into your smelter:

1. Human breath through blowpipes.
2. Wind.
3. Natural draft.
4. Bellows or other "blowing" machinery.

Let's look at them one by one

Human Breath Through Blowpipes

This was certainly done in antiquity, here is the proof. The picture is from the tomb of Mereruka in Saqqara, Egypt and dates to the 6th dynasty, 2 450 BC - 2 350 BC; Use this link to see the full picture.

Supplying air with blowpipes

Source: Photographed in-situ

- If those guys are melting gold / copper or are smelting something, we don't know. My bet is on melting gold.

Blowpipes are easy to make. Just take a hollow reed and smear some clay on the hot side. They are also rather inefficient for the following reasons:

1. Exhaled air contains considerably less oxygen than normal air, something like 14 % instead of 21 %. Then it contains carbon dioxide (about 5 % instead of 0.04 %) and around 6 % water. So it not only supplies less of the important oxygen but adds useless stuff that will absorb heat. The maximum temperatures achievable therefore are only around (1 500 - 1 300) ^{o}C, quite low compared to the achievable 2 000 ^{o}C with a sufficient supply of regular air.
2. Even a trained (male) adult will not get a substantial amount of air into the fire; at best around 75 liters per minute (0.075 m^3/min) are possible.
3. You can't easily make up for these deficiencies by having more guys with blowpipes blowing into a given hearth. There is just not enough space. Making the blowpipes longer, allowing for a second tier of blowers, increases their air resistance and thus deceases their efficiency.

Nevertheless, if you have ever blown on a fire, you know that it makes a big difference. It is safe to assume that early smelting and melting was done in small crucibles or bowls with the aid of blowpipes. Here are few additional facts and numbers:

- A small crucible with about 25 cm inner diameter (a salad bowl) needs about four well-operated blowpipes if you want to smelt / melt copper or melt gold. That goes well with the picture above and a few archaeological finds. It would in all likelihood not be good enough for smelting iron.
The problem is that there are not many archaeological remains of blowipes. Organic matter like reed will not last for thousands of years, and what is left of crucibles / bowls mostly does not tell us what it was used for. Pieces of a bowl that was used for melting copper 6000 years ago do not look much different from pieces used for smelting.
- Smelting copper, however, would tend to be an erratic and inefficient operation. Poor slag fluidicy because of low and fluctuating temperatures, less then optimal reduction conditions, and so on, more often than not produced just some copper **prills**, little roundish pieces, entrapped in a viscous slag.
On a positive side, those copper prills were not contaminated with iron, a bad thing, because that only happens at high temperatures. The iron gets into the smelter because it is almost always present in the gangue. Often iron oxide was even intentionally added as a good flux.
- In South America, it appears, smelting and melting of copper / bronze was always done with blowpipes; bellows were unknown. That is probably the main reason why smelting of iron was never done and the use of copper / bronze was rather limited.
- The general prejudice that temperatures in antiquity did not exceed 1 200 ^{o}C (2 192 ^{o}F) may have its origin in the limitations of blowpipes.

Natural Draft and Wind

The reverberatory furnace shown here can heat substantial amounts of load to temperatures far above 1 200 ^{o}C (2 192 ^{o}F), and 1400 ^{o}C (2552 ^{o}F) are definitely obtainable. You don't even need charcoal, dry wood is enough. It just serves to show that it is perfectly possible in principle to supply enough air for major smelting operations by natural draft, making good use of the chimney or stack effect.While a reverberatory furnace as shown was not possible in antiquity, simpler constructions were and could achieve high temperatures. Pottery kilns, also mostly operating with wood and natural drafts were widely used, for example.

- However, natural draft furnaces for smelting were used but not on a large scale, it appears. Again, it is difficult to tell because the remains of an old furnace are typically a few stones in the ground and its precise construction and how the air supply was handled cannot be told.

Remains of a smelter

Source: Photographed in the Goslar museum

- In Africa, natural draft iron smelters were used until "recently", but that was more the exception than the rule.

Compared to a bellows-operated smelter, a natural draft furnace needs several tuyeres with rather large inner diameters to produce the necessary air space velocity. That is already a certain complication and might have contributed to the unexpectedly scarce use in antiquity. Other problematic points are:

- Large tuyeres do not produce high air velocities, and the penetration of the air into the charcoal bed might have been insufficient, producing inhomogeneous results.
- Air leaks in the body of the smelter are far more serious than for bellow operated smelters and made the building and maintenance of a smelter more difficult. Not much more difficult, however. The problem is the know-how. If you don't know that this little hole up there is the cause for bad smelting results, and it appears that ancient smelter operators did not, you do tend to dislike air-draft smelters. If you do know, stuffing it up is easily done.
- A chimney, i.e. a long cylinder on top of your smelter that might be needed to produce enough draft, makes "feeding" your smelter through the top rather difficult.
- Most serious, perhaps, is that a natural draft-smelter either works or does not. You simply have *no control* anymore, there is no button to turn to adjust something. In contrast, with a bellows-operated smelter you can work your bellows harder or more leisurely. In other words: you do have some control over the air supply, the main parameter in smelting.

- However. if you do not want to *s* melt but just to *melt* something or fire your pottery, some of those problems disappear. You achieve higher temperatures automatically because you do not have all that ore and flux that suck out energy from the heat flow, and you typically can see what is going on through some peep hole, so you know when your copper / bronze / gold / silver is liquid.

It is hard to imagine that the bronze for very large cast bronze parts - e.g. the parts of the **Colossus of Rhodes** - were not molten in air-draft furnaces, build on the spot and dismantled after use. No remains would be found.

Colossus of Rhodes.

Source: 16th-century engraving by Martin Heemskerck, Internet

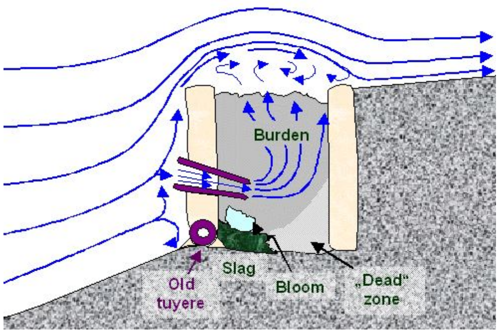
- The colossus was erected 305 BC, was over 30 meters (98.4 ft) tall, and was made from about 500 "talents" bronze (15 tons) and 300 talents iron (9 tons). It counted as one of the Seven Wonders of the Ancient World.
  The costs were 300 talents silver (9 tons), about 4.5 Mio Euro at todays silver price. Considering that silver was probably more expensive then, while the cost of labor was far lower, it probably would take ten times that amount today. Building the 46 m (151 feet) tall Statue of Liberty today would run up a bill around $50 Mio - despite our modern techniques for making and moving things!

Wind Furnace

When a natural draft furnace with tuyeres all around its lower circumference experiences a gush of wind, not much happens. True, more air is blown into the tuyere facing the wind, but on the back or lee side, air is sucked out and the effects more or less cancel. If you want to make a true "wind furnace", you need two things:

1. Reliable wind in sufficient strength blowing constantly for some time, and always from the same direction.
2. An asymmetric furnace with lots of tuyeres that are all pointing in wind direction.

Something like this, in other words:



Wind furnace on Sri Lanka; about 50 cm high

Source: After G. Juleff: "An ancient wind-powered iron smelting technology on Sri Lanka", Nature 370(4), 1996, p.60 - 63

This is the cross-section of a wind-powered furnace from around 400 BC, unearthed in Sri Lanka and shown to be able to smelt iron in some reconstruction. It is build into a hillside, almost two meters long, and equipped with 14 tuyeres. Its performance was lousy but very high temperatures could be reached close to a tuyere. High-carbon iron was produced
"*This technology sustained a major industry in this area during the first millennium AD, and may have contributed to South Asia's early pre-eminence in steel production*" is the claim. I doubt that very much.

As always, after you have found a recipe that works, it does just that: it works. If you repeat *exactly* what you were doing the first time, you will ge the same result. However, you will never be able to repeat what you did *exactly*, and there is such a thing as a "process window", defining the tolerances of your process to small variations in process parameters. Good processes have large process windows and some "buttons" or controls that you can turn to keep the process within the process window, where things proceed nicely.
Wind-powered smelters have small process windows; they are just as bad or even worse than natural draft furnaces. You have not much influence on what is going on after you set your wind-furnace on fire, and you certainly cannot control the wind. Your wind-furnace will work ever so often but there are better (and cheaper) ways of smelting iron.

Bellows and Other "Blowing" Machinery

The word "bellows" stems from late Old English "belg", meaning bag, purse, leathern bottle. It comes from the same root as the German "balg" (= hide, e.g for making goatskin winebags or bellows); or "belly".
You probably associate a bellows with something like this:

Big bellows in the "Neue Hütte Schmalkalden"

Source: Photographed right there

This is already an advanced and rather large leather "accordion" bellows, worked by a powerful water wheel. In ancient times, however, a bellows might just have been a leather bag with an opening (sort of what powers bagpipes), a ceramic bowl with a hole and a membrane, or (especially in China) something akin to your bicycle pump. Whatever, distinction in bellows comes from these points:

- Is there a *valve*? Closing when you blow out the air, and opening up when you fill your bellows? A valve avoids sucking out the air from where you just blew it in when you open up your bellows. A valve is a good thing to have, rather obviously, but not so easy to implement with early leather and wood technology.
- One stroke or *two strokes*? Do you just blow in air when you push it together, or also when you pull it out again? Two-stroke bellows are clearly much better because they deliver a more steady airstream. They are more difficult to make, though.
- Airtight or leaky? It is not so easy to make bellows completely airtight without proper tools and materials.
- How large is its *efficiency*? How many percent of the mechanical work put into its operation goes into producing airflow in the end?

The earliest clay pot bellows come up with a meager 15 % efficiency. A well-trained slave can deliver a mechanical power of 120 W, with $120 \cdot 0.15 = 18$ W then being converted into moving air. Going through the numbers, that produces about **3.6 m^3** airflow per minute!

That is about 50 times more than what a guy with a blowpipe can do!

- **Bellows efficiencies** much better than 15 % are easily possible, and it is very clear now why smelting metals *in bulk* simply is not economical without some kind of bellows. As already noted, this is likely the reason why the South American cultures never smelted iron and didn't do too much with copper and bronze either. *They never invented bellows*.
    - Leather and wood bellows will not survive for thousands of years, so it is not totally clear when and where they have been invented. Egyptian tomb pictures show only blowpipes before the Hyksos or Hittites invaded Egypt around 1670 BC. After that humiliating experience bellows appear in paintings, and iron in everyday life. This can be seen as strong evidence that the Hittites knew bellows before they invaded Egypt, and that this knowledge might have been instrumental in making the Hittites the first masters of iron smelting.
    By the way, in all of the extensive writings found in Egypt (and these guys really covered every available flat surface with their hieroglyphics), there isn't a single mention that Egypt lost major wars and was occupied by the Hittites for a while. According to Egyptian history writings, they never lost a war and were always on top of everybody else. Those guys were already rather advanced and modern, it seems, and the Pharaohs evidently commanded large public relation departments.
- Smelting with one or a few man-powered bellows could produce large quantities of metal and that's why any serious ancient metal industry relied on air supply by bellows.
    - The next step then seems to be clear. As soon as mechanical power by water wheels became available (e.g. in the Roman empire), far surpassing he 120 W of human power, they were used to work big bellows (like the one shown above). Air supply to smelters took another big leap, and large smelters could be build and operated. Well - yes! It would have been possible *but it wasn't done!* It would not have made sense because nobody would have been able to deal with monstrously large "blooms", the mass of iron produced in large smelters. You couldn't lift it, transport it, or, most important, forge it into something useful with only a hammer and muscle power. So smelters remained small for another thousand years or so.