Smelting Science

2. Charcoal Technology

A New Look at Charcoal

How charcoals are made I have described elsewhere, so look it up. Here I will address questions like "are all charcoals created equal?" or "What makes a charcoal-fueled fire different from a wood fire?".
Charcoal, for starters, can be made from most carbon containing stuff (you included) but the quality of what you get depends on what you start with *and* how you processed it.

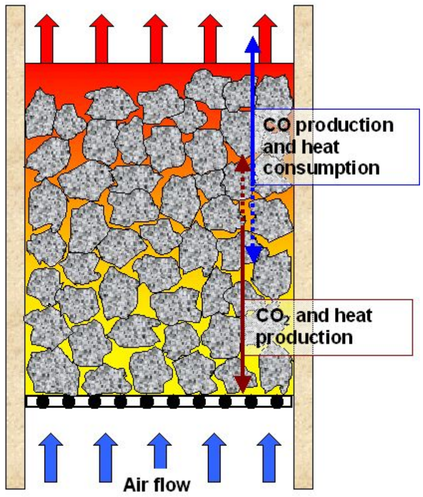
- The quality of charcoal suitable for smelting will differ from that destined for barbecuing spare ribs. Parameters of prime interest are.

  - ***Density***; related to porosity. Higher porosity means less density, more surface area and less mechanical strength. The density of charcoal is between 180 kg/m^3 and 280 kg/m^3
  - *Carbon content* in %. Processing wood to charcoal around 500 ^{o}C (932^{o}F) yields about 80 % - 85 % carbon content; at (more expensive) 900 ^{o}C (1 652^{o}F) 90 % - 95 % might be obtained.
  - *Energy content*. Around 28 MJ/*kg* and thus considerably more than (dry) wood at around 20 MJ/kg. That allows for higher maximal temperatures T_{max} of up to 2 000^{o}C (3 632^{o}F). Note that the energy content *per volume* varies with the density.
  - *Average lump size*. Quite important because you want to have a rather well defined lump size of the charcoals you feed into you smelter.
  - *Chemical reactivity*. An important parameter depending on many things (in other words: I'm not so sure about that). In any case, the chemical reactivity of charcoal, i.e. how easily it burns, is rather large compared to other forms of carbon and goes up with increasing porosity / more surface area.
  - *Hardness / mechanical stability*. That is very important because you don't want your lumps of charcoal to fracture into smaller parts during handling or transport, or under the weight of the ore / charcoal mixture (the "**burden**", as it is called), that sits atop of the burning stuff in your smelter.
  - *Conversion efficiency*, i.e. how much of the total weight of the fuel / wood processed is regained as charcoal. With modern processes a conversion efficiency of 35 % to at the very best 50 % is achievable. In antiquity, however, the conversion efficiency was more like 10 % - 15 %.
  - *Dryness*. Charcoal easily absorbs water and everything else. That increases its density and brings down the energy content. This is usually bad but there are occasions when it might be advantageous.
  - *Prize*. You pay for the making and the transport. Unfortunately, good smelting charcoal will be rather on the more expensive side.

- A few rules that go with these parameters are:

  - *Hardwood* makes denser and stronger charcoal than *softwood*. But softwood charcoal might have a higher reactivity since it is more porous. Some biomass produces only charcoal "dust", it is not useful for smelting.
  - Processing wood at *higher temperatures* makes stronger but less reactive charcoal at lower yields and thus at a higher prize.
  - Small-sized wood from *twigs* and *branches* makes harder, denser and less reactive charcoal than wood split from big tree trunks.

Now conceive a "bed " of proper charcoal pieces, all having roughly the same (proper) size. The free volume or "inter-lump void fraction" then is around 40 %, allowing air to pass with an air flow resistance that is rather small and not limiting air flow. For the sake of simplicity assume that the air flow is uniform and comes from *below*; requiring that your bed of charcoal sits on some kind of griddle or grate. That is *not* what happens in real smelters but close enough and far easier to deal with.



Burning charcoal bed

- If everything is done right, *all* the oxygen contained in the air supplied will be consumed by the very reactive charcoal fuel within the first few layers (at most about 10) according to
$C + O_2 \Rightarrow CO_2$ + energy. **Carbon dioxide** and energy heating up everything is produced!
This reaction is very fast, practically instantaneous.
The higher charcoal layers are also quite hot since they get heated by the hot gas produced (**N_2** and **CO_2**), They cannot burn because of the lack of oxygen so a new reaction takes place:
$CO_2 + C$ + energy $\Leftrightarrow$ 2 CO. Carbon monoxide is produced and energy is consumed. This cools everything to some extent
This reaction can easily go both ways, hence the double arrow. At a given temperature there is some equilibrium betwen the concetration of carbon dioxide and monoxide. At low temperature CO_2 prevails as the reaction product, at high temperatures of at least 1000 ^oC (1832 ^oF) carbon monoxide prevails. And carbon monoxide is the reducing agent per excellence!

We have generated strongly reducing conditions on top of the first few layers of the charcoal bed!

- Here we have the main reason why charcoal was so important for early smelting. Doing this with wood is pretty much impossible. Coke can do the same trick but charcoal is more reactive and easier to work with. Smelting with charcoal has been done up to the 20th century!
  - The carbon monoxide producing reaction is also known as **Boudouard reaction**. It actually needs energy to proceed and that's why it will not take place in sufficient quantities at low temperatures. You need high temperatures as noted above. The concentration of carbon monoxide in a smelter is at best around 21 % (there is always lots of nitrogen around) but something like 12 % is more realistic since the reaction takes time and not all of the CO_2 will be converted while it passes through the bed of hot enough charcoals.

Working with Charcoal

- The smelting master must see to it that the right kind of lump size is provided. As a rule of thumb, the average charcoal size should not be larger than about 8 % of the inner diameter of the furnace. It shouldn't be too small either since this increases the air resistance and for the same reason it should not contain a large spectrum of particle sizes, allowing smaller pieces to fill the interstices between the larger ones. The average **lump size of your charcoal** sort of defines the lengths scale in your smelter.
  - The charcoal used should have properties "just right" with respect to the peculiarities of you smelter. That might call for a mix of more reactive but less dense light wood charcoal with hard wood charcoal. Small wonder that smelting masters, after having determined the best mix from many runs, were inclined never to change their recipes. Here is an actual recipe from the 19th century.
  - They also tended to be very conservative for another reason. In pretty much most of antiquity, the ore - flux - charcoal mix was done by volume: two baskets of ore, one basket of flux, ... This was far easier then doing it by weight, and why should one, in the first place?

- For smelting you need about as much or more charcoal by *weight* than ore. Since the density of charcoal is only about 200 kg/m^3, just a few percent of that of typical ores (iron ores, e.g., are around 5 200 kg/m^3), your burden consists mostly of charcoal by *volume*. And now you have a problem! How do you get all this charcoal to your smelter? Charcoal is actually an extremely wasteful energy carrier. Consider: From all the wood you cut down, only about 15 % end up as charcoal. It might be even worse if you go only for one kind of wood and only for branches of a certain size. If you run a sizeable operation, you will have exhausted the woods around your smelter rather quickly. Then you either need to take a break of 30 years or so to regrow some trees, have charcoals shipped to you from appreciable distances, or move your smelter
    - So let's ship the charcoal. Fine - but how? We do not have good roads and trucks. Remember: we live in antiquity. Moving stuff is mostly done by ship, indeed - hence "shipping" even in modern lingo - or by oxcart. Both methods are optimized for heavy loads (like ore), not for light weight stuff, and thus extremely uneconomical for moving charcoal.
      If you have to move your charcoal for more than 10 km, say, it is typically easier to move your (small) smelter. Here you have a reason why large scale smelting requires coke that you make on the spot from the coal you dig out in large quantities right where you are. The ore then needs to be shipped but that is much more economical than shipping charcoal / coke.
- The need for large quantities of charcoal (and wood) is one of the reasons why European forests disappeared to a large extent already at Roman times. In order to make things a bit easier, **coppicing** (pronounced: KAH-piss-ing) was invented millenia ago. It was (and is) used on a large scale in England.

Coppiced "Woods"

    - Coppicing involves cutting down a young tree near ground level in such a way that new shoots grow from the stump or stool. The procedure than is repeated periodically, possibly for hundreds of years. You simply produce more wood in a given area this way.
      Coppicing works. However, from a German point of view, it is disgusting. What is left cannot be called a proper forest anymore. Maybe a weak character like Goldilocks can do her thing in coppiced woods but Red Riding Hood, Haensel and Gretel, or Siegfried and the dragon are unthinkable in this kind of degeneracy. The first law of economics still applies.