

The science of wood combustion

HOWARD W EMMONS and ARVIND ATREYA

Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

Abstract. The purpose of this paper is to provide an introduction to the physical processes involved in the combustion of wood and other cellulosic fuels. This introduction is aimed towards the utilization of the cellulosic fuels as an energy source. A discussion of a design of the stove is also provided to aid the development of such a device.

Keywords. Pyrolysis; flames; charburning; heat; stove.

1. Introduction

Fire from natural causes has been known to man and animals from the beginnings of life on earth. A momentous event occurred when man discovered that fire could be controlled and used in many ways. The easy availability of wood and other cellulosic materials has provided an abundance of natural, renewable energy resource.

Even before fire was tamed, man no doubt knew that wood subject to fire first produced white smoke, then flamed, then glowed as a pile of embers and then cooled off as a small pile of grey ashes. Today with our extensive knowledge of the physical laws which govern the universe, our scientific knowledge of many of the details of the wood burning process has begun to be clarified but is far from complete. In this paper, we will briefly review some of what is now known about the burning properties of wood and the resultant fire.

The next major step in understanding combustion of any material is summarized in the fire triangle (figure 1). This emphasizes in a very useful way the essential components which permit a fire to continue to grow or by the control of which a fire can be extinguished. All three components—fuel, air and heat—are needed to start a fire, and the mixing of these three components is equally important. By removing the fuel, by smothering (removing the air), or by cooling (spray it with water), a fire may be extinguished. Useful as this picture is, it is still not fire science.

2. The science of fire

Perhaps a word would be useful at this point to make clear what we mean by a scientific understanding of fire (Emmons 1980) (or any other phenomena). A complete scientific understanding would make it possible to not only describe qualitatively what happens but to quantitatively calculate exactly what happens from beginning to end. We will not try to write the required book to present what is now quantitatively known but will rather review briefly each of the steps in a fire.

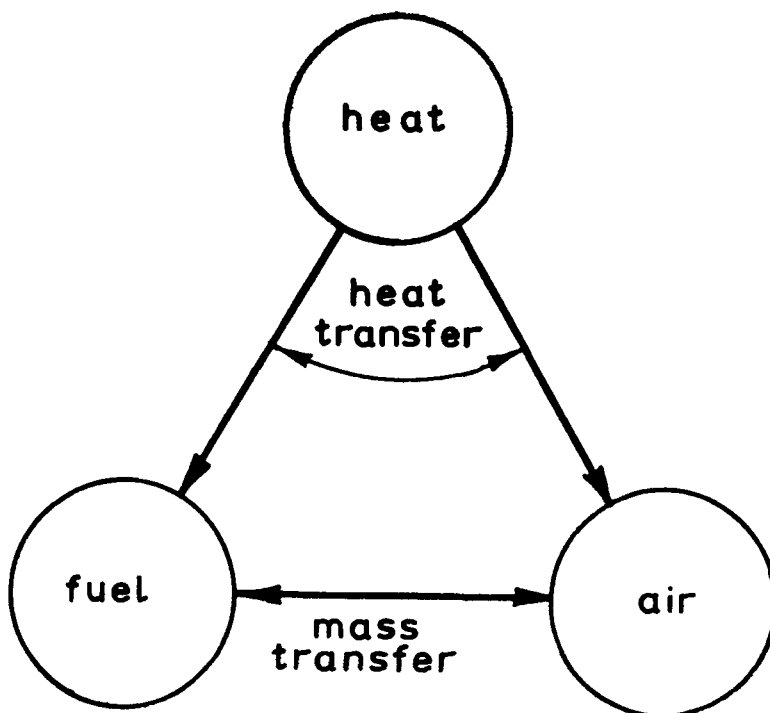


Figure 1. The fire triangle.

3. Pyrolysis

Wood, like all material bodies, is composed of atoms attached to one another. In wood, the atoms are attached to one another in strings thousands of units long. The cellulose molecule, as these long strings of atoms are known, is a polymer (Shafizadeh 1981; Modorsky 1975; Stamm 1964; Goos 1952). It doesn't happen to be one which man can yet make but nature makes it with ease. Wood is made of these cellulose molecules and other molecules called lignin. These are arranged by the growing tree into a cellular form—a natural cellular plastic.

Like all materials composed mostly of atoms of carbon, hydrogen and oxygen, they are held together by interatomic forces. The temperature of a material is a measure of the violence of the atomic motions in the molecule. As the temperature of a material is raised, the atoms vibrate more and more vigorously. Eventually, the atoms vibrate so strongly that they separate, *i.e.*, the molecule begins to come apart. The weakest linkage is between units of glucose, a group of 21 atoms. However, many other fragments are also produced and many of these fragments are very active chemically and join together again into new stable combinations. The detailed chemistry of the thousands of reactions between hundreds of chemical species is far from understood at the present time.

From a fire point of view, the carbon that is left behind as charcoal is the only solid produced by wood pyrolysis. All other materials are the gases that mix with air and burn as a flame.

This complex chemistry occurs as the wood becomes hotter. However, as we all know, the wood in a fire soon turns black. The pyrolysis of the wood surface leaves a char layer of carbon and ash which then shields the interior virgin wood from direct heating from outside. Now the radiant heat from the fire falling on the surface of the char must conduct down through the char layer to heat and pyrolyse more virgin wood.

When wood is pyrolysed below a layer of char, the gaseous products produced have to get away somehow. Some merely diffuse through the layer of char. Since wood shrinks when it is changed to char, the char layer cracks. Some of the new pyrolysis gases flow out through the cracks in the char. This results in the hissing sound and the jet flames that one sees in an open wood fire. Some of the gases diffuse away from the surface into the virgin wood through the natural pores and there condense, to be repyrolysed later (Min 1975). Finally, those gases unable to escape remain in the pores and raise the internal gas pressure. The mechanical strength of the charring wood is soon exceeded and a small piece of glowing char is violently expelled from the fire. This process accounts for all the snapping and popping we always hear in a wood fire.

Wood begins to pyrolyse significantly at about 250°C and very actively at about 325°C.

Pyrolysis is of central importance in flaming combustion of wood. Not enough is yet known about this complex process to assure us of a proper quantitative prediction of the mass pyrolysis rate. Numerous researchers have worked on this subject, notable among these are: Bamford *et al* (1946), Akita (1956), Roberts & Clough (1963), Tang & Neil (1964), Tinney (1965), Martin (1965), Broido (1966), Kanury & Blackshear (1970), Roberts (1970), Walker (1970), Havens *et al* (1971), Roberts (1971), Kung (1972), Kung & Kalelkar (1973), Kung (1974), Shivadev & Emmons (1974), Kindelan & Williams (1975), Lee *et al* (1976), Kansa *et al* (1977), Shafizadeh (1981).

In spite of this long list of important studies, useful results of the pyrolysis process are still almost entirely empirical.

4. The flames

The gases produced by pyrolysis consist of some 213 different compounds (Goos 1952; Modorsky 1975; Hileman *et al* 1976), some are very simple like carbon dioxide, carbon monoxide, and water, and some are complex organic molecules of 20 atoms or more. As these gases issue from the wood, they are hot, they have lower density than the surrounding air, and therefore these gases rise. As they rise, they mix with air and either cool off and partially condense into smoke or, if ignited, burn as a flame.

The flames from wood are almost wholly yellow in the optical wavelengths but also produce a lot of 'heat radiation' in the infrared (De Ris 1978; Modak 1977). The flames directly spread the fire upward by convective heating of pyrolysable fuels above them and heat the walls of the stove which warms the room. Far more important, however, is the radiant heating. In particular, the size and intensity of the flames themselves are controlled by the pyrolysis of the original fuel by the heat supplied from its own flames. Fire is an energy feedback process in which energy

from the flames heats and pyrolyses the fuel, that supplies the gases, that mix with the air and burn, thus radiating energy which heats and pyrolyses the fuel, etc., etc. The radiated energy also heats other as yet unignited fuel to spread the fire and heats the walls of a stove or furnace, thus supplying the heat to cook our food and heat our dwellings.

The reaction of fuel with oxygen of the air occurs in two places; one is on the surface of the glowing charcoal and the other is in the flames. The exact chemical processes taking place in the flames is so complex that it has not yet been clarified except for a few (unimportant) cases. Even the burning of hydrogen in oxygen to produce water is kinetically too complex to be fully clarified as yet.

What is understood is that the initial reactions in the lower part of the flames produce a great deal of carbon monoxide and free carbon. The carbon agglomerates into small soot particles that are responsible for much of the energy radiated. The carbon monoxide and soot then reacts in the upper part of the flame that cools by the energy radiated. If the radiation is too high, the soot does not burn up but leaves the flames as the black micrometer size particles which joins any smoke present and moves away from the fire. All kinds of wood produce enough soot to produce yellow flames, but few woods fail to burn all the soot before it gets out of the flames, provided there is excess oxygen available. The production of soot in flames is an active research area at the present time (Glassman & Yaccarino 1981; Lee & Tien 1981). This is important and will be noted again later in connection with the design and operation of stoves.

5. The smoke

The large molecules in the pyrolysis gases which mix with air but are not ignited condense into tiny micrometer-size droplets. The mixture of these and the uncondensed gases has the familiar smell and appearance of wood smoke. This has many effects. As the smoke moves up the chimney, it deposits on the walls and can later cause a serious chimney fire. As it accumulates in the stove, the ignition may be delayed until the smoke is thick enough to be flammable, after which it may burn rapidly in a small explosion. If the smoke gets into the house, perhaps from an unwanted fire, it will make it difficult to see and breathe. In fact, many of the organic compounds in smoke are highly toxic, so that most people who die in fires are killed by the toxic gas, not by the heat of the fire. Finally, some of the compounds in wood smoke are known carcinogens. Thus, long term cancerous effects of breathing smoke are possible, although to our knowledge has not yet been proven.

6. The air

The discussion above assumes that the pyrolysis gases find air with which to mix and burn. Air is 21% oxygen and 79% atmospheric nitrogen (includes 1% argon and small amounts of other gases). As the gas in a flame rises above its source, the turbulent eddies mix it with the surrounding gases. Then, above the flames, the products of combustion, the atmospheric nitrogen, and unused oxygen move away from the fire.

This brings us to the question as to where the air comes from and where the flue gases go. In the open, the camp fire, the flames draw the air in from around the base and the hot product gases buoyantly rise away at the top. In a stove, however, provision must be made to admit the air in the place and the amount required. In an industrial furnace, the air and fuel flow are driven by a fan and a pump respectively. In a household wood burning stove, the fuel—wood—is put in every time someone thinks to check on the fire. The air is generally drawn in and the flue gases are removed by a chimney. The chimney takes the place of the industrial fan. The fact that the products of combustion are hot causes them to be lighter than air and hence they rise up through the vertical chimney and draw new air in at the bottom. The performance of a chimney depends upon the outside temperature, wind and surrounding structures, if any.

The air flow through a stove thus depends upon the performance of the chimney. However, it also depends upon the tightness of the house. If a house were built with no leaks around the windows and doors, the chimney would be unable to draw air through the stove, since there is no air supply below. It would merely reduce the pressure in the house. The fire would soon go out for want of oxygen. Almost no houses are really tight.

There is no reason to expect that the performance of the chimney and the leaks of the house give exactly the right air flow for a stove. Thus, further discussion of air flow control for a stove will be appropriate later.

7. The char

When discussing pyrolysis, we noted that the thermal decomposition of wood produced gases and char. The char amount varies with the kind of wood from 20 to 30% of the weight of the wood (Broido & Nelson 1975). Char, or charcoal, is largely carbon but contains small amounts of hydrogen and oxygen together with all the ash of the wood (Shafizadeh 1981). Carbon does not melt at ordinary pressures and changes to a gas (sublimes) at a very high temperature, 4000°C. Thus, the char, when it burns, reacts with oxygen on its surface. Since it is usually cracked and is always porous, the reacting 'surfaces' are largely inside.

Glowing char radiates a lot of energy. Unless there is a lot of oxygen present, it will soon radiate its energy away, will cool off and go out. As we all know, blowing at glowing charcoal (Evans 1975) makes it burn brighter and the fire spreads to adjacent areas. What we are doing is supplying more oxygen and the carbon responds by reacting faster. We also all know that if we had blown at the same rate at a match, the fire would be blown out. The flame gases can be blown away while the hot charcoal surface cannot move but instead reacts faster with the additional oxygen supplied. The burning of the charcoal is very important since about 30 to 60% of the heat of combustion of the wood is available from burning the char.

We spoke of burning the char in oxygen. In fact, the carbon being in great excess on the char surface produces mostly carbon monoxide, which, when it mixes with air and burns, produces the little bluish flames seen over the surface of a charcoal fire. Thus in fact a significant amount of char surface burning is carbon reacting with carbon dioxide to produce carbon monoxide which, being a gas, burns in a flame above the surface.

8. The heat

Wood primarily contains lignocellulosic materials, along with various extractives ($\sim 7\%$ dry basis), minerals and moisture. These components vary for different parts and species of the plant, for example, soft wood and bark contain more lignin than hard woods. The presence of lower molecular wt extractives (turpentine components) in natural fuels helps flaming combustion, since they readily evaporate. Both lignin (heat of combustion about 27,000 kJ/kg) and extractives (heat of combustion about 35,000 kJ/kg) have a higher heat of combustion than cellulose (about 17,000 kJ/kg) because of their lower degree of oxidation. For most fuels, chars, and volatiles, the heat of combustion correlates roughly with its carbon content as

$$\Delta H^{25^\circ\text{C}} = [394.1 (\% \text{ C}) + 230.2] \text{ kJ/kg.}$$

This correlation is due to mutual cancellation of increase in heat content because of the presence of a greater number of hydrogen atoms in some fuels, and decrease because of the presence of oxygen in others. There are, of course, some extreme cases like CO_2 . The heat of combustion of various natural fuels is given in table 1 (Shafizadeh 1981). The last column shows the heat of combustion of volatiles that are released. These burn in a flame with only about 70% combustion efficiency in free-burning fires. Combustion efficiency can be increased by increase in turbulent

Table 1. The heat of combustion of natural fuels and their pyrolysis products as char and combustible volatiles.

Fuel		Char		Combustible volatiles		
Source	Type	25° ΔH comb (kJ/Kg)	Yield%* 25° ΔH comb (kJ/kg)	Yield%* 25° ΔH comb (kJ/kg)	25° ΔH comb (kJ/kg)	
Cellulose	Filter paper	-17334	14.9	-29506	85.1	-15205
Douglas fir lignin	Klason	-26656	59.0	-31029	41.0	-20364
Popular wood						
<i>Populus</i> ssp.	Excelsior	-19322	21.7	-29807	78.3	-16414
Larch wood						
<i>Larix occidentalis</i>	Heart wood	-19456	26.7	-29995	73.3	-15615
Decomposed douglas fir						
<i>Pseudotsuga menzeisii</i>	Punky wood	-21422	41.8	-29472	58.2	-15640
Ponderosa pine						
<i>Pinus ponderosa</i>	Needles	-21527	37.0	-27564	63.0	-17983
Aspen						
<i>Populus tremulosdes</i>	Foliage	-21062	37.8	-26543	62.2	-17732
Douglas fir bark						
<i>Pseudotsuga menzeisii</i>	Outer (dead)	-21430	52.8	-24259	47.2	-18267
Douglas fir bark						
<i>Pseudotsuga menzeisii</i>	Whole	-23882	47.1	-26803	52.9	-21284

*Heating rate 200°/min to 400°C and held for 10 min.

mixing and by providing some excess air. When the air supply falls below that stoichiometrically required, then the combustion is said to be ventilation-controlled. Numerous data (Harmathy 1972; Gross & Robertson 1965) on burning of wood piles in enclosures have shown that the rate of mass loss of the fuel is directly proportional to the supply of oxygen. In such a case, the heat release rate can be calculated by oxygen consumption. Krause (1979) have shown that within $\pm 5\%$, heat released is 420 kJ/kg mole of O_2 for combustion reactions at 25°C to form various products.

9. The ash

A few percent of the weight of wood are various mineral substances that do not burn and are left over after all combustibles are removed. For the campfire, the ash is no problem; it is simply left behind to help fertilize the new growth. However, in a stove, the ash accumulates and after a few hundred pounds of wood are consumed, the stove has begun to fill up with the fluffy grey ash. Thus steps have to be taken to remove the ash. Wood ashes contain potassium carbonate which is an important fertilizer element and is good for the garden.

10. The stove

We have now touched briefly on all the aspects of the burning of wood. The details of the processes are understood more deeply than described above but the essential features have been introduced. The importance of these features is that they will all occur when wood is burned, whether we like it or not. Since they will all occur, we should design the stove so that they occur efficiently.

What do we mean, "efficiently"? The purpose of a stove is to provide heat at its top surface for the preparation of food and to provide heat for the warming of our dwellings in winter. A 100% efficient system would use all of the heat of combustion of wood, and put it to a useful purpose in the house. This is not possible since heat is the motive power which produces the chimney draft. Furthermore, the air used by the fire must be heated up to the flue gas temperature using some of the fire's energy. Since dwelling comfort is one purpose of a stove, there are two ways to supply combustion air to the stove. The usual way is to take the air from the living space. This requires new cold outside air to come into the living space, thus producing uncomfortable drafts. This is poor design. A much better design, but one almost never used, is to have a connection to the stove directly from out of doors. Such an air supply would avoid drafts in the house but would be expensive and generally inconvenient.

The internal stove problems of "efficiency" are far more important and more difficult. In the first place, let us note that the energy feedback from the flames to the fuel is not an energy loss since it is returned in full measure when the fuel burns.

The real problem arises when we wish to regulate the rate of burning to fit our needs. We of course can build a large stove or a small one. The right size is not just one which can burn wood at the required maximum rate and no faster, but one which can hold a sufficient charge of wood so that it does not need recharging every few minutes.

But here is the first major difficulty. Suppose a charge of wood able to supply the required heat for overnight can be accommodated in the stove. What is to prevent the fire from growing very rapidly throughout the wood supply and consuming it in the first few hours? We cannot control the internal energy transfers between sticks and thus control the fire growth. The only practical control is the air supply. Thus dampers (valves in the air supply system) are used to adjust the air flow.

This controls the rate of fire growth all right. However, it does so by preventing the rapid burning of charcoal and by controlling the heat release in the flames. This reduces the energy feedback to the fuel, thus reducing its pyrolysis, which is what we wanted. However, the control of the heat release in the flames was accomplished by supplying insufficient air to efficiently burn all the fuel.

In most stoves, the air is admitted in the front near the bottom. Thus what flames there are still cause considerable wood pyrolysis, the flame combustion that is controlled is the burning of the pyrolysis gases at the top and back of the wood supply. These gases, mostly as smoke, go up the chimney unburned, a very inefficient process.

A few stove designs attempt to correct this loss without too rapid a fire build-up by admitting more air at the rear. The idea is good and it would no doubt work if there was an observation window at the back and someone continually regulated the extra air. For efficiency, the extra air should just burn all the smoke but nothing more. Any leftover air is a loss since it takes energy to heat it, only to lose it up the chimney. But even this would not be enough. Since the air at the front has been cut down to prevent rapid fire growth, the smoke and gases at the rear of the wood supply are no longer hot enough to burn even if more air is added.

In fact, for fire control, the smoke and gases must be below the pyrolysis temperature or the wood would still be pyrolysing too fast. Thus, to burn the exhaust gases with more air also requires a pilot flame to guarantee that they ignite. No stove to our knowledge has provided any rear ignition source.

How can this problem be solved? There are only two possible ways; either limit the wood as well as the air, or instal a rear air supply and an ignition source. Neither of these is practical so that all stoves are very inefficient as actually used and fill the chimney with flammable deposits. These deposits must be removed annually to prevent chimney fires.

Steps can be taken to get heat out of the hot gases into the air of the room. To do this requires a lot of heat transfer surface. The surface of the stove itself is generally not large enough to cool the flue gas down to a few hundred degrees (sufficient for good chimney action). Thus a few extra lengths of stove pipe between the stove and the chimney can remove the extra heat from the flue gases before they are lost up the flue.

Why not do away with the air supply at the front of the stove and control combustion at the rear. This would not guarantee wood pyrolysis at the desired rate and would make it difficult to keep a fire burning. It is essential to burn the charcoal produced in a fire and this requires a flow of air over the char surface. It is therefore customary to stack coal or leftover charcoal in front and wood at the back. Thus a front air supply is essential.

Finally, different kinds of woods differ greatly in their ease of ignition and rapidity of burning. This is particularly true of the effect of moisture in wood. Green wood can only be burned in a rapidly burning fire which can "dry it out" before it must

burn to continue the fire. Thus the best air supply to a stove must be experimentally determined using the actual wood available.

At various times in history, stoves were made of ceramics. This is fair for cooking purposes, but for home heating it is very poor because the low thermal conductivity of the ceramic keeps the heat inside instead of transferring it outside where it is wanted. The best stoves are made of thick (1/8 inch or more) sheet steel, welded at all joints so as to be airtight. Then a tight-fitting door is added to provide supply port for the wood. Finally, air holes are added at the desired locations. These should have a good screw type cover for air flow adjustment.

What about the future? It is possible to develop an electronic device (a computer chip) which would continuously monitor the fire efficiency and regulate amount and location of the air supply to guarantee high performance. This we say is possible, it's not clear that it will ever be economically worth doing.

11. Conclusions

Wood, when exposed to heat, pyrolyzes to produce hundreds of compounds that burn in a flame about it. These flames feed energy back to pyrolyze more material. As a result of pyrolysis, a charcoal layer is formed which thermally protects the virgin wood below it. This charcoal layer becomes thicker, reducing the supply of gaseous fuel and thus the vigour of flaming combustion. During this process, if oxygen is available, it reacts with the hot char to promote glowing combustion. In a stove, all these processes would occur simultaneously. The current scientific understanding of these component phenomenon is not mature enough to provide a reliable quantitative prediction, but, nevertheless, is very useful to provide direction. The final design of a stove should be determined experimentally for the available bio-fuel guided by what is currently known of the science of fire.

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