The Combustion of Wood
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The combustion of wood is a somewhat complex process to be described by the written word.

Wood, a product of photosynthesis, is predominately composed of cellulose and lignin that are made up of carbon, hydrogen, and oxygen. Combustion is the reversal of photosynthesis.

$$\mathbf{6(H_2O) + 6(CO_2) + sun \rightarrow C_6H_2O_6 + 6O_2 = burning + O_2 \rightarrow CO_2 + H_2O.}$$

One may say the plants convert the sun's energy into a storable fuel in the form of wood which mankind accesses through the use of fire.

The chemistry and physics of combustion is very complex due to the many processes going on at the same time. On ignition, the first step is to drive out moisture at the energy cost of 1200 BTUs per pound of water vaporized. We detect a bit of gas production because we can smell something. As long as there is excess moisture to be boiled off the temperature of the wood fuel does not rise above the boiling point of water.

Due to the insulation properties inherent in the wood heat conduction to the interior is slowed and only a thin surface layer of the piece of wood can be affected, and chars when dry enough. Even at 540º F, ignition is subdued because of the high concentrations of non-combustibles in the mixture of carbon dioxide and water vapor evolving from deeper layers. For ignition at this stage a temperature of 1000º F to 1200º F is needed.

Shortly, water vapor is virtually eliminated, and what now holds back combustion is any lack of O_2. The stifling action of the gas mixture excludes oxygen and holds back spontaneous ignition, requiring a some nearby flame to start the piece burning in order to generate temperatures ranging from 1600º F to 2000º F, providing there is adequate oxygen.

With more heat, more gasses (volatiles) form and smoke evolves in considerable amounts. When the ignition temperature is reached (300-400º F or150 – 205 ºC) an external flame will ignite them. These volatiles or vapors and gasses can be condensed into the pungent-oily-liquid creosote and a thick tar.

Further breakdown (pyrolysis) evolves more combustibles that ignite on their own if hot enough at a spontaneous ignition temperature of 600º F (315 ºC) so that smoke production is reduced and self-sustaining heat is more efficiently produced.

As more volatiles blaze away (unless the pyrolysis is purposely carried out in a closed vessel that excludes oxygen to distill the products of pyrolysis) carbon forms and eventually begins to glow, with an intensity about 3 ½ times greater than the normally visible flames of combustion, a property so useful in flint and steel fire lighting and in heating iron in blacksmithing.

Soon the flaming stops and glowing persists at a temperature of 1000º to 3000º F. When the carbon is consumed incombustible white ash is all that remains.

Charcoal vaporizes at temperatures well above that achieved in a wood fire but still glows if sufficient oxygen plays upon the surface, only after all the gasses have been driven out of the wood.

At 900º F the charcoal develops a barely visible bluish glow sustained by carbon monoxide that has an unusual property of burning without a luminous flame. The initial faint glow of charcoal is much like the glow of an electric element or a piece of iron heated in a forge – the surface not burning until much higher temperatures are reached.

Charcoal is not pure carbon as it contains some hydrogen, oxygen and a few minerals. As the carbon is consumed the components in the gaseous compounds evolve as ash that is practically all that is left after a good fire.

In maximizing a fuel's potential heating capability about 1/3 to 2/3's of the woods energy of combustion is tied up in producing gasses and vapors. For the most heat from your fuel avoid producing the somewhat noxious byproducts as much as possible by operating your stove properly.

Through pyrolysis we produce valuable by-products like charcoal for blacksmithing, creosote for wood preservatives, and wood gas for running a vehicle, but if produced in your stove these are a curse to be avoided to get the most heat out of your fuel.

Generally, the quicker wood is burned, the more gasses and tar, and the less charcoal is produced. The production of flaming gasses an charcoal depends on a number of factors:

- The intensity of the fire (the type of enclosure allowing or excluding O_2)
- The type of wood (BTUs directly related to dry weight)
- The moisture content ideal range (15% to 25%) (26 % too wet) (14 % too dry)
- The sizes of the pieces (neither too big nor too small)
- Proper loading of the fire box

A smoldering (flameless) fire will lose 20-40% of the woods energy up the chimney as unburned smoke so the challenge is to efficiently combust the volatiles produced. The charcoal accounting for about half the potential heat stays in place as it burns so it presents no problem. When new wood is added at peak heat, the hotter surroundings dry and vaporize the fuel that much faster.

Combustion is a chemical reaction, mainly involving oxygen, fuel, high-enough temperatures and the formation of highly reactive radicles. Heat evolves as combustion progresses, the amount depending on the rate of reaction, which in turn is dependant on the ability of molecules of fuel and oxygen to mix together in the proper proportions. The most rapid combustion is an explosion and the slowest a smolder.

A wood surface at 180º C (356º F) is apt to ignite spontaneously as happens when a hot enough water pipe is passed through a wooden beam.

The ease of ignition is related to how finely one divides the fuel. With two samples of equal weight, one having a surface area of one square meter, and the other of ten square meters, the square meter takes ten times longer to burn up but the finer material will reach much higher temperatures in its shorter burn but the amount of heat produced remains the same.

Understanding how wood burns and how a stove controls combustion improves your insights on how to get the most heat out of your wood burning stove.

Combustion in a stove is rapid but not instantaneous oxidation of various substances.
Oxygen in the air is 20.91% by volume and 23.15% by weight. When it is reduced to 16% any fire goes out and a human suffocates.
Carbon – a combustible non-metallic element generally found in organic compounds
Oxygen – supports combustion
Hydrogen – a combustible, colorless, odorless, tasteless gas, lightest element known
Sulphur – inflammable, easily melted, easily ignited to a blue flame that gives off a peculiar suffocating odor
Nitrogen – odorless, tasteless, colorless, non-combustible gas, that is non-supportive of combustion, or life. The amount of heat of combustion used to raise the temperature of the nitrogen is a dead loss. It sets a low limit to the temperature reached by combustion in air. The heat lost to nitrogen is reduced by excluding excess air from the firebox. In an atmosphere of pure oxygen a fire would burn five times as fast.
BTU – The British Thermal Unit is the amount of heat it takes to heat one pound of water one degree Fahrenheit. This is close to the amount of heat produced by one large kitchen match burned up completely. A pound dry wood, regardless of the species yields about 8,000 BTUs.
Combustion – oxygen ignites with the hydrogen in a material first because of a stronger affinity. The carbon is released and becomes incandescence in the hydrogen flame, and with the oxygen forms carbon dioxide, carbon monoxide (combining to make carbonic acid) and when starved, carbon or soot as well. A restricted fire producing carbon monoxide provides 4,450 BTUs, with adequate oxygen and heat it produces carbon dioxide providing 14,544 BTUs – a 1,106 BTU's difference!
Moisture – green wood is harder to burn and wastes energy boiling off the higher water content. Live or green wood may have as much as 65% of its weight made up of water and sap. Normal air-dry wood has about 20% moisture for a 3.5% net loss of heat. If 50% moisture remains the loss is 8.6%. A pound of completely dry wood will yield 7,950 BTUs. Each pound of water in each charge of stove wood causes a loss of 1200 BTUs. The steam from the moisture dilutes the combustion gasses to increase tar and soot buildup. When felling, delaying the trimming of branches and their leaves for a few

days helps draw out some moisture. It takes from 6 to 12 months to adequately dry cut-to-length stove wood.

Flame Velocities – Blowing at a flame can extinguish it if the velocity of the air exceeds the flame velocity of the burning gasses. An ignitable gas will burn quietly if fed into air as it is burned, but if it is first mixed with the air and then ignited explosions tend to occur. This combustion becomes so rapid that the flame velocity exceeds that of sound. The differentiation between burning and an explosion is the former is less than and the latter is greater than the velocity of sound.

Stages of Combustion in a Stove

Stage (1) Driving out Moisture: When fuel is heated to the boiling point of water (212º F, 100º C) heat is being used up to the rate of 1500 + 100 or 1600 BTUs per pound.

Stage (2) Pyrolysis: 350 to 540º F. There are chemical changes in the character of the wood. Heat is being used. Creosote if formed from pyro ligneous acid which is a combination of acetic acid, formic acid, wood alcohol and carbon.

Stage (3) The Burning of Tars and Gases: At 600 to 700º F solid wood ignites, but until the gasses evolved are included in the combustion the fire is not fully developed. At 1100º F the volatiles burn and heat is produced.

Stage (4) Burning of Charcoal: Up to 2000º F charcoal begins to give up the last half of the potential energy of the wood. Charcoal melts at 6,300, boils at 7,600º F.

Difference between Stoves & Fireplaces

An open outdoor fire and an indoor fireplace operate in a similar way. The output of such fires depends on the number of logs burning together. In unrestricted air situations 90% of the heat produced goes up the chimney (10% efficiency). In a stove, the retention of air and the heat holding or heat emitting structure of the stove allows as little as 40% and as much 60% on the average

Stove Size

In **s**electing too small a stove for the space one wants to heat, a hotter fire will be necessary. This is good as there is less of a tendency to use smoldering creosote and soot producing fires to avoid overheating the room but you may burn out your stove prematurely.

Choice of Stove Size

Considerations:

- Is it the sole source of heating or is it backing up an existing furnace?
- Must it provide warmth for long periods without stoking (as the household sleeps) for up to nine hours and still have enough coals to continue burning without relighting or is frequency stoking not a serious issue?
- Is the space the stove is to occupy sufficiently large to accommodate the fire code?
- Do you seek a condition where it would be quite difficult to set fire to the home if the stove operates at maximum?

The Airtight Stove: There are basically two major types of stove – the airtight and the older non-airtight. The airtight stove's main feature is its good control of the entrance of oxygen into its firebox. It can be more precisely set to an oxygen-to-fuel ratio providing enough air to sustain the fire to last as long as possible and derive maximum heat from your wood. There is an optimal air-to-fuel setting one may have to establish through trial and error.

When too much air (too rich in oxygen, also too much nitrogen) is supplied, it dilutes the gasses and cools the stove. The carbon can not combine with oxygen at a rate exceeding two atoms of oxygen with one atom of carbon.

With insufficient air there is a tendency to slow the fire enough that excessive creosote, noxious gasses and soot are formed. The cooler stove and chimney more effectively condense these undesirables.

Firing Up an Airtight Stove: First warm the stove for a short while and get the fire well established before making any adjustments to extend the fire. Avoid choking down the airtight too much without taking into consideration the management of polluting smoke and excessive formation of creosote and soot. When the stove is as warm as it gets for your setting and white smoke belches from the chimney, open the inlets some more until the smoke is reduced.

Maintaining a Safe Efficient Clean Burn

***The best of stoves suffers from unskilled operation*.**

Starting the Fire:
The objective of starting with fine kindling and fuel is to get going quickly and with some strength. This is to develop a draw in the smokestack and to warm the stove and smokestack, to an operating temperature as quickly as possible. Charge the firebox first with the heavier kindling, then with the finest on top so that it is not compressed.

A firebox that is jam-packed usually evolves a sooty, smoky, creosote-laden fire. A modest fuel load burns better.

After the fire is well underway the charge should consist of a minimum of two or three pieces of fuel more or less filling the firebox but not touching the sides to develop a reinforcing mutual radiation, spaced at the width of a finger so that the pieces are close enough to concentrate heat and spaced enough to allow the access of oxygen for combustion. THIS EXACTLY APPLIES TO OPEN FIRES AS WELL.

The intensity of the fire is generally related to the size o firewood used. If attempting to use a too small stove to warm a large space, the use of a constant too high fire usually damages the internal components of the stove.

Burping in Airtight Stoves

When a well-made airtight stove is closed down completely from a hot burn, the air is suddenly cut off but volatilization continues for a short time and updraft suction through the stove pipe slows down or stops. Oxygen then works its way down the chimney and flash ignites the volatiles causing enough internal pressure to push smoke out of the firebox into the room.

Long (Banked) Fires

If long banked fires are to be frequently engaged in, choose a big enough stove in the first place. With a sufficiently large capacity firebox and an efficient airtightness with a refined air inlet (throttle) it is possible to create a slow fire lasting as long as nine hours when the household is asleep or away from the home.

Stove Efficiencies

A stove has two efficiencies for consideration:

1) The efficiency of combustion.
2) The efficiency of transferring its heat to its surroundings.

For combustion efficiency a controlled air supply is needed and the stove must be able to form and mix the combustible gasses evolving from the fuel which often involves a primary and a secondary burn. From half to two thirds of the wood's energy is contained in the released and combusted gasses, and the remainder evolves from infrared radiation. Fuel efficiency may account for up to a 20% saving in wood – a substantial monetary saving.

Airtight Stoves vs. Conventional Stoves

Most airtight stoves have internal design features to improve on secondary burning of the unconsumed gasses that have escaped the primary burn, thus consuming less wood than conventional stoves.

As conventional stoves allow more air around the door and have simpler air intakes the control of the speed of burning is carried out by a damper in the smokestack leading out of the stove. By partially blocking the outflow of the products of combustion, there is more opportunity for them to burn up.

The Second Efficiency

-There is an effective transfer of heat to the region surrounding a stove.

-To transfer heat effectively the stove has to have large conductive walls and a long stove pipe. Such a large stove may overheat a small house in a mild climate, so a smaller stove is more convenient to use.

-A stove claiming 80% efficiency is very good but there is a possibility that the claim is exaggerated. A claim of 30-75% is more realistic.

Controlling the Air Supply

-The amount of air let into the firebox to support combustion is fairly set. Too much or too little air will cool the gasses either by cooling or starving the fire itself. The more airtight a stove, the more effectively it will burn large pieces of fuel.

-A well designed air inlet provides for a maximum temperature at the half way point of its adjustment so that it can be fully opened to start a fire, and be fully closed to extinguish it as well as adjusting for various loads of wood.
-There is considerable merit in using a flue thermometer installed close to the flue collar to monitor combustion temperatures to assist in making better adjustments. A functional range is about 350 to 800º F in normal operations.

Attitudes & Expectations in Using Stoves It takes some time to realize how far back you have to revert to a more basic process. There is a tendency by learners to apply misconceptions on how to operate a stove that may have something to do with thermostats on the one hand and being familiar with open fires on the other. Wood burning routine has its demands that do not often jibe well with a modern lifestyle attitude. Some people attempt to use the learning they have achieved in using open fires to try to run a wood stove and thereby do poorly.

Hit and Miss Fire Building
The Hot & Cool Approach:
1. Kindle fire
2. Charge firebox as full as possible
3. Let charge burn to coals
4. Charge firebox as full as possible again
5. Reduce the number of door openings
6. Let fire sit at coal burning stage for longer periods
7. Allow the chimney to cool between stoking
8. Cause unnecessary smoldering due to the fuel touching hot walls

The Improved Constantly-Hot Approach Fuel added before active flaming subsides – to maintain a fire that is hot enough to prevent undue creosote formation and to encourage rapid evaporation of fuel moisture.

Suggested Good Stovemanship

The Three 'T's of Combustion
1. Create a <u>temperature</u> high enough to initiate good combustion
2. Provision of sufficient *<u>turbulence</u> through appropriate stove design* to mix combustible gasses
3. Provision of sufficient <u>time</u> for combustion to occur by retarding the outflow of combustibles out of the stove.

-The fire needs the right amount of space to burn. Too little inhibits the flame too much and radiant transfer is not optimal.
-The overly full firebox has a reduced turbulence for O_2 so that mixing results in considerably more incomplete combustion. The more wood put in the stove, the more it will burn with a reduced charcoal stage, and the less complete the combustion resulting the more ash and unburned charcoal.
-Fill the firebox only from ½ to 2/3 full.

-Keep the fuel away from the inside surfaces of the firebox – if the flame touches metal, it may cause some carbon monoxide to form.
-Split wood in such sizes that the above is accomplished with three or more sticks (once the stove is going well.)
-A reasonable expectation is a larger stove may burn about two hours on a good stoking and a smaller winter camping stove for 45 minutes. Some mistakenly assume that a small wood stove should go eight hours between stoking!
-A given amount of fuel needs a given amount of air to burn, no more, no less.
-If the stove gets too much air, you are wasting fuel by heating air.
-If the fire does not get enough air, incomplete combustion results with an excess of smoke and creosote, the former contributes to pollution and the latter to the possibility of a chimney or stove-pipe fire.
-If the air combines with fuel too quickly, the flame is too hot. At temperature over 1800º F nitrogen reacts with oxygen and other unwanted chemicals form, wasting energy and creating toxic substances.
-Check out how much smoke is coming out of the chimney and adjust accordingly but keep in mind that constant high firing can damage the stove's internal components.

Signs of a Properly Maintained Fire
-Wood should always be producing flame until charcoal remains.
-Interior of stove should not be black (usually tan).
-Instant ignition as you charge the stove on the newly formed bed of coals is a good sign.
-A glass door should not be tarring up.
-Chimney exhaust should be clear or white.

Creosote: Creosote is not necessarily produced in greater quantities from resinous woods. Poor 'secondary' burns can contribute to creosote production. Proper sizing of stove pipes is important. All woods closely (not exactly 15-20%) dry or moist, produce the same amount of creosote. Wet woods produce a bit more – the hydrogen content in wood is released so that a pound of any wood will produce about a half pound of water.

Effectiveness of Radiant Stoves vs. Circulating Stoves
Both circulating and radiant stoves have their relative merits depending upon the design of your home and how much heating they need to deliver. A circulating stove is basically a shrouded radiant stove. The shroud has openings at the top and bottom, allowing air to circulate between the firebox and the jacket which sets up natural convection around the stove and the space to be heated.

Most of the heat transferred from a circulating stove warms the *air* while heat transferred via radiating stove heats *objects*. (Neither of these statements is absolute.) In a poorly insulated house a radiant stove can warm you just as the sun does. A circulator gives a more homogenous heat that surrounds you on all side. Less heat loss occurs with a radiant stove. A well insulated and weatherproofed home shelter or tent will improve the performance of any stove.

Circulating stoves tend to ‘dry out’ air; the heating capability for radiating stoves is enhanced when humidity is high. There is considerable merit in keeping a small pot of water set on the stove to assist with the humidity.

Walls are a major obstacle to heat transfer. One large room heats more easily than three smaller rooms of the same total size through their doors. In circulating heaters the air flow must work itself through doorways and around corners to reach remote areas. These stoves heat objects not air. A large room where people spend much of their time, is best warmed by radiant heat. A large rambler with many walls for the heat to penetrate would be better served by a circulating stove. Convective energy transfer is more efficient in providing more homogenous or even temperatures. If you spend a lot of time in one room, or in a large open area, the radiant stove is adequate, but to heat an entire house you will get a more evenly heated home with a circulating stove. Radiant heaters are located away from combustible surfaces and as far away from windows as possible. If children are present, a circulators outer jacket is usually not hot enough to burn a hand.

Smoke: Smoke from a wood fire is scant if the stove is well designed, the fuel as good as it can be, and the operator a knowledgeable fire tender. What comes out of a chimney is a mixture of inert nitrogen, unused oxygen and a very large list of the chemicals forged in the combustion process.
-Troublesome aspects of smoke relate to the discomfort of breathing it in and it affecting the eyes. One does not become accustomed to smoke in the eyes, you become more and more sensitive. Improper factors in the given elements of the stove’s design may create high levels of dangerous by products such as carbon monoxide.
-Mishandled combustion can cause the condensation of the byproducts of combustion to create creosote and soot deposits that cause destructive chimney fires. An open fire does not produce a fraction of the dangerous pollutants that may evolve from a badly adjusted stove. An oxygen starved fire produces thick grey, brown or black smoke. In a good fire the smoke is almost white and translucent.

Reading the Fire through a Stove Window
Smoldering – too little oxygen
Roaring – too much oxygen
Adequate oxygen is determined by flue gas temperatures which should be above 400 to 900º F. Firebox temperatures are about one half of flue 250 to 475º F. A flue thermometer is highly recommended

Disadvantages of Wood Heating
Wood is feasible as the only fuel for home heating only if it is reasonably inexpensive and readily available.

1. Part of one’s property has to be given over to growing, processing and storing wood.
2. A good portion of the heated room has to be given over to the stove.
3. Wood has to be split and carried in with its consequent messiness.
4. Ashes have to be unloaded, stored and disposed of.

5. Smoke escaping during stoking and ash dust will affect TVs, video & DVD players and fax machines.
6. Indoor pollution is possible.
7. Stove has to be tended frequently which is disruptive and time consuming.
8. There are safety issues concerning house fire, chopping and splitting with an axe, chain saw use and procuring and storing its fuel, and chimney cleaning.
9. Chimney maintenance is messy and it has to be cleaned regularly. You must have access to the roof and be able to climb it safely.
10. Cost of transporting wood in – ashes out.
11. Wood brought indoors may bring in insects with it.
12. The physical exertion of cutting, loading, splitting, carrying firewood indoors is much less convenient than twiddling a thermostat.

The Danger of Red Hot Stoves

There is a danger of heating stoves red hot, especially if made with cast iron as this may create cyanide. It has been found that cast iron under such circumstances is permeable to the gasses of combustion. Tests prove the existence of the highly poisonous carbon monoxide in the immediate vicinity of the stove; and, where the ventilation is insufficient, throughout the atmosphere of the room.

It is supposed also that the oxygen of the atmosphere combines, to a certain extent, with the carbon of the iron, so as to increase the percentage of carbon monoxide. The primary remedy against this problem is to have the stove lined internally with brick or some substance other than cast iron.