Combustion and Heat Transfer in a Rocket Stove System

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The object of this paper is to create a simple understanding of combustion and heat transfer. Good construction and operation of a rocket stove should be based on this knowledge.

One of the first things to recognize is that solid or liquid material does not burn directly. They must be converted to gasses in order to burn. Most biomass is hydrocarbons which, when heated convert to oil and oil vapors of many different types. Some oils are visible or smelled even before the biomass is heated. For example, fragrances, turpentine, pitch, etc. Green, wet wood may contain as much as it's dry weight in water. In order to burn water must be evaporated. This uses up about 1000 BTUs of energy to evaporate each pound of water. At sea level and atmospheric pressure the temperature of boiling water is limited to 212 degrees fahrenheit. Similarly heat energy must be provided to evaporate or distill each of the hydrocarbons formed from the wood. The lighter hydrocarbons are easier to change to the gas phase, heavier hydrocarbons like creosote take more energy, however if too much fuel surface is heated and the gases cool before they can intermingle and ignite with hot air or oxygen they will condense back into a fog our cloud of oil droplets. This is the smoke that we see. It is analogas to the fog or cloud that forms when water vapor condenses. Heat must re-evaporate the oil droplets before they can burn.

After many different types of oils are evaporated only charcoal remains. The hot charcoal first reacts with oxygen to form gaseous carbon monoxide. Then the carbon monoxide burns with the air to make carbon dioxide. Carbon dioxide is the final result of a clean burn. Smoke and carbon monoxide are wasted fuel. It is possible to run a car engine using this as fuel. During the 2nd World War over 1,000,000 vehicles were converted to run on "smoke" and carbon monoxide.

If a fire is very hot and there is excess hot carbon some water can be broken down into hydrogen and oxygen. For about 100 years until natural gas (methane) big cities made their own fuel gas, mainly a mixture of carbon monoxide, hydrogen and some lighter hydrocarbons.

A very creative Alabama cattle rancher (Wayne Keith) has resurrected and improved the forgotten wood fired car technology. He has published several "youtube" videos. He has converted at least 6 vehicles to run on wood gas. Wood gas powered vehicles are his principal form of transportation. He has driven a total of over 200,000 miles on wood gas. He holds the official US speed record for a wood gas vehicle. It has been said that he gets a better conversion of the energy available in the wood into traction power than a typical engine gets from running on fossil fuels. I think this could be true because Wayne salvages much of the waste heat to preheat the air used in the gasifier. I do not think this was done in the past. He also cools down the gasfier gas by exchanging heat with the incoming air. The more heat he can salvage, the less fuel he has to burn to make the wood gas!

In the past an engine running on wood gas suffered about 40% loss in power. Waynes conversions only lose about 25%. His big dodge pickups get about 1 mile/lb of wood. His smaller ford F-150 gets about 1.5 miles/lb of wood.

Many different types of fuel can be used in the rocket stove if one understands how the burning process works and uses the proper grate and placement of fuel. Sticks of wood work best if several are placed together on the shelf with a little air space between them. If they touch the back wall, they should be pulled back about 1/4 inch. (This important trick was shown to me by Gustavo Pena)

The sticks close together will radiate heat back and forth since the glowing surface of each stick is about the same temperature, little heat is lost. It is kind of like several people in bed together.

Flat pieces of fuel, like shingles of wood or cow dung patties should be placed on edge with air spaces between them. Charcoal that is produced should be suspended (preferably on a grate) until it burns to ash. The purpose of the rocket stove is to get as much energy as possible out of the fuel converted to useful heat. It is NOT meant to produce charcoal or biochar.

Some fuels with a high ash content like cow dung, some biomass briquettes and some coal briquettes have such a high ash content that the left over ash can be a fragile sintered mass that may replicate the shape of the fuel. This mass must be removed or it will block the air flow. Small pieces of fuel like sawdust, rice husks, coffee husks, seeds, nuts, nutshells, etc can best be burned with an inclined grate like the conifer sawdust burner (Still being manufactured by HERN ironworks in Coeur d'Alene Idaho). In this burner sawdust flows out of an adjustable slot near the bottom of the hopper on to an inclined grate that is made of approximately horizontal flat bars. This resembles an open flight of stairs. These "stairs" can have adjustable angles like window blinds or louvers.

Sawdust or other fuel particles fall out of the door slot and build up on the inclined plate until the flow out of the door slot is blocked. Primary air is sucked through the glowing coals and fresh sawdust gasifying the fuel. Preheated secondary air is directed into the smoky fuel gases and immediately produces a clean burning flame. As the particles on the inclined grate burn up, the door slot is unblocked and fresh particles slide onto the grate, when the grate angles are adjusted to the type of particles, the process is automatic, working entirely by gravity and the natural draft of the chiminey.

After the arab oil embargo in the 1970's, I experimented a lot with wood gas for using waste materials to provide energy for many applications. These include running a D-8 Cat Engine, driving a Ford f-150 and running a 0.049 model airplane engine on cigarette smoke. These experiences make me appreciate very much what Wayne Keith has done.

In the early 1980's I learned about the need for simple affordable fuel-efficient stoves to help poor people from aprovecho. In order to create such a stove, I developed a set of combustion and heat transfer principles so local materials could be used to build the stoves in most parts of the world.

I mentored Dean Still at Aprovecho and he, working with a factory in China, now make rocket stoves that ship all over the world. My good friend the late Ken Goyer , the founder of Aid Africa, and I developed a insulating 6 brick rocket stove to help the refugees in Uganda. Aid Africa stove making continues and improves under Peter Keller, Executive Director of Aid Africa. John and Flip Anderson, A husband and wife team that I mentor, have become world experts making rocket stoves, ovens and kilns from clay and organic materials. They could not make the ETHOS conference because they are in Haiti. They have generously put their work on YouTube and Flip's picture album. They have pictures of the clay rocket pizza oven that heats to baking temperatures very fast compared to a traditional clay oven. With a chiminey extension it can reach temperatures over 1200 deg Fahrenheit and fire clay parts for other rocket stoves.

Rocket stove designs consider both combustion efficiency and heat transfer efficiency. A key feature of Rocket Stoves is that the fuel is easily metered in so that only as much surface is heated as necessary for the power production, for wood this means that only the ends are gasified and burn in the vertical combustion chamber. This is in effect a very hot chimney that pulls air in at a moderate velocity. In the horizontal feed rocket stove the wood rests on a shelf with the ends overhanging, forming a grate, or they can rest on a real grate at that position. Some air comes from underneath the shelf in the feed tunnel and up through the glowing ends of the sticks where gasification takes place. "Secondary air" comes in over the shelf and in between the sticks. This air keeps the sticks cool and helps keep the flames blown into the vertical chimney so that the fire does not back out the feed tunnel. The same principles apply in the down feed or "J" shaped rocket. In this the sticks tend to self feed as the end's burn off. Fuels like grass and corn stalks, reeds can burn like sticks of wood if they are twisted or braided together to minimize the exposed surface. Sawdust or particle fuels can be fed on to an inclined grate like the conifer burner discussed earlier.

Biomass briquettes slightly smaller than the width of the feed tunnel but with a hole in them can be burned. The first briquette is lighted on the end that goes into the chimney. Rok has made several videos showing this.

Sawdust can be tamped into a reusable container around a dowel to make a "holey" sawdust briquette. A small stick of wood, burning inside the holes of the sawdust briquettes helps serve as a pilot flame.

Good convection heat transfer is very important in the rocket stove.

A domestic rocket stove needs a feed tube cross section of about 20 square inches and a chimney height of 12 inches.   This means that the cooking surface is too far away from the coals to receive much radiant heat.   The advantage means that the fire has time to complete combustion without the chilling effect of the cooking pot.

In convection heat transfer as packets of hot molecules touch the surface of the pot, they quickly cool down and slightly raise the surface temperature of the pot as they reach a new equilibrium. Since the molecules and the pot's surface are essentially at the same temperature they can no longer transfer heat to the pot's surface. So it is better that they be replaced by a new fresh group of hot molecules. This is why we want the hot combustion gases to slide as close as possible without choking the flow. We do this by keeping the momentum of the gas flow as constant as possible. Any change in momentum would use up part of the small pressure force provided by the chimney draft. Keeping the cross sectional area of the gas flow constant essentially means the speed of the gas is constant thus there is less change in momentum (i.e. less choking of the flow). Since momentum is a vector quantity, just changing direction will require an impulse of a pressure force and a slight loss in draft pressure.

Keeping the cross sectional area constant under the pot means that we can taper the slope of the top of the stove. This gets the gases to flow closer and closer to the bottom of the pot. When we put a skirt around the pot with a gap adjusted to have the same cross sectional area we heat the sides of the pot effectively. As the gases cool down, they become more dense, so the cross sectional area could be reduced slightly and still have the same momentum.

This is the primary purpose of the pot skirt. Some say that the pot skirt is a wind screen or that it is used to control excess air. This is a misunderstanding of it's primary purpose.