Thoughts on Mixing Pyrolysis Gas and Secondary Air

In the TLUD Cooking Stove

This document results from my years of experiments with the TLUD type biomass cooking stove. It includes observations, hypothesis, and conclusions from my experiments, and thoughts about the principles which I feel contributed to successful stove designs. Some statements have a basis in my experimental observations, but lack scientific confirmation by professional scientists and engineers. I offer the exceptional performance of the stoves, measured at Aprovecho, as evidence to support consideration of the presented concepts. Hopefully, the document will present areas which need further research.

This is a working document and is constantly changing as better information arises or to improve clarity.

Kirk Harris

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by Kirk Harris

The TLUD cooking stove is a gas stove that makes its own gas by pyrolyzing solid biomass fuel. The fuel is first processed into small chunks, which are piled into the stove’s fuel/pyrolysis chamber. This fuel pile is ignited at the top, and a hot layer, called a migratory pyrolytic front, begins moving slowly downward. The volatiles in the solid fuel are vaporized in this layer, producing pyrolysis gas. The non-volatile char remains above the pyrolytic front as a solid. To enable this pyrolysis, a small amount of air (called primary air) is allowed in at the bottom of the fuel chamber, and allowed to pass up through the spaces between the fuel pieces to the pyrolytic front. Just enough air is allowed in to burn a small amount of the pyrolysis gas and char at the pyrolytic front, producing just enough heat to keep the biomass fuel pyrolyzing. The resulting, mostly unburned hot gas rises by buoyancy to a burner where it is mixed with air (called secondary air) and ignited to combust its flammable components. The burner is specifically designed to burn the hot pyrolysis gas emerging directly out of the pyrolysis chamber. The pyrolysis gas is complex, containing solids, liquids, vapors, and gasses, so careful design is important for clean burning. To attain efficient burning of the pyrolysis gas, a main interest is the efficient mixing of the pyrolysis gas with the secondary air. Efficient and rapid mixing leads to shorter, hotter, and more efficient flames. This document is a discussion of the mixing and burning of gasses in the TLUD biomass cook stove, with special attention to the very effective Venturi mixing technique.

**Some basic principles that are important for mixing gasses in a TLUD:**

1. The gasses must be brought together to be mixed. The amount of **contact surface** between the gasses determines how much gas can burn all at once.
2. **Depth of penetration**: The secondary air must penetrate into the pyrolysis gas. Forming the gas for less penetration depth allows faster, more complete mixing.
3. The pressure difference (gradient) between the gas and air forces them together. More **pressure gradient** means more penetration and faster mixing.
4. **Permeability** of the gasses is important to allow penetration and blending.
5. Sufficient **Contact time** will achieve as much mixing and combustion as possible.
6. The **direction of impact**: parallel; no mixing, head-on or angled; better mixing
7. **Temperature** of the gasses; closer together works better for mixing and higher is better for burning.

The above principles are important considerations for the following mixing techniques.

**Turbulence Mixing:** The draft gets the pyrolysis gas moving up through the TLUD, and once the gasses are moving turbulence is possible. Turbulence physically disrupts the flow of the gasses with vortexes and eddies, created as the gas passes a turbulator device. Principles which help turbulence to work are the increase of surface contact and decrease of penetration depth, which result when intertwined regions of the separate gasses form. Since there is no pressure gradient between these regions to force the gasses together, diffusion is relied on to progress the gasses from this regional mixing to uniform molecular mixing. This process can take time and space to get a substantial mix, and depending on the quality of the turbulence and the dwell time, often the mix is incomplete. It is susceptible to uneven and non-stochiometric mixes. Turbulence mixing is present in many TLUD flames.

**Diffusion Mixing:** Diffusion mixing occurs whether the gasses are moving or not. The random motion of the molecules in the gasses gradually, by random chance, mixes the gasses. This process is slow, but becomes faster at higher temperatures when the molecules are moving faster. It is present in all TLUD flames.

**Concentrator mixing:**

The gas and air can be brought together and mixed by passing them through a reduced diameter hole in a metal plate, a concentrator. This technique is simple, inexpensive, and effective, making it an excellent technique for small mass-produced cook stoves. Dr. Paul Anderson explains the principles which make the concentrator work:

*I see the concentrator lid / disk as restricting the area of mixing, causing the speed of flow of the secondary air and gases to be faster per unit of area where the air and gas are mixing, compared to the more “lazy” mixing when the area is greater. Also, the smaller (concentrated) area means less distance to travel before meeting the flows from the opposite and lateral directions.*

*In this natural draft situation, the shape/size of the chimney segment above the hole in the concentrator is what controls the power or forces.*

**A unique characteristic of concentrator mixing:** The concentrator mixing technique works beautifully within its design range. It does have a unique and interesting characteristic. As the power level is turned up, there is more gas and less air. As the power level is turned down there is less gas and more air. This is backwards of the way it needs to be. With more gas and less air, a point is reached where the mixture is too rich, leading to smoke and soot. With less gas and more air, a point is reached where the mixture is too lean and cool, leading to the flame being extinguished.

So, what is going on? I found a possible explanation in something I noticed in my experiments.

I noticed over numerous tests an occurrence which left me confused for some time. My stove designs have multiple burners, small, medium, and large to allow a range of power levels. The confusion had to do with the low power burner, which consists of holes in the side of the pyrolysis chamber, just under a concentrator.

At low power levels, with low primary air, and low pyrolysis gas production, the flames at these burners were large.

When I turned up the power level, making more pyrolysis gas, the flames at these burners became smaller. I had expected the increased draft and gas would make them larger.

After examining pressure variations inside the TLUD, I saw a characteristic which could cause this, by what I refer to as a **backward pressure gradient**. As the pyrolysis gas impacts the concentrator ring, it slows down, increasing its pressure by the Venturi effect. This pressure increase is directly in front of the secondary air inlet. The increased pressure pushes back on and reduces the incoming secondary air. As the pyrolysis gas decreases, this pressure decreases allowing in more air.

LESS GAS >

LESS PRESSURE > allows in MORE AIR > BIGGER FLAME

MORE GAS >

MORE PRESSURE > allows in LESS AIR >

SMALLER FLAME

**How a backward pressure gradient could affect a concentrator mixer**

I hypothesize that the concentrator mixer carries the backward pressure gradient to an extreme.

More gas = too little air

As the power level and pyrolysis gas increases, the pressure under the concentrator increases, resisting secondary air entry, the mix is too rich, and smoke and soot form

Less gas = too much air

As the power level and gas decreases the pressure decreases, letting in too much secondary air, the mix is too lean and cool, and the flame is extinguished

Good mixing within the designed power range

Concentrator mixer advantages:

* Simple and easy to build
* Inexpensive
* Effective within its designed power range

Disadvantages:

* Limited power range, due to backwards pressure gradient

For my low power burner, backwards pressure gradient would affect only a small portion of the gas and flame, only changing the flame size. For the concentrator mixer, it would affect the whole flame, so the effect would be more impactful, creating smoke or extinguishing the flame.

**Pressure Gradient Mixing:** Gasses flow from higher-pressure to lower-pressure, following the pressure gradient. The greater the pressure difference, the greater the force driving the flow. In a TLUD, as in any flame, the pyrolysis gas pressure is lower than atmospheric air pressure, forming a pressure gradient which the secondary air follows into the stove and into the pyrolysis gas. Since the gasses are permeable, the secondary air can penetrate into and blend with the gas. The gasses can quickly mix on a uniform molecular level.

Pressure gradient mixing includes any mechanism which creates or increases the pressure difference between the gasses. It is present in all TLUD fires.

The natural draft mixing techniques of turbulence, diffusion, and pressure gradient mixing occur together, in varying strengths, in most all combustion. Example: what we call the diffusion flame actually contains considerable pressure gradient mixing.

**Sources of pressure gradients in a TLUD stove**: My experiments showed two types of pressure variations. Most sources effect the pressure at large, but the Venturi effect produces very localized pressure variations.

**The Buoyant force (draft)**: The initial force which gets the gasses moving and begins the mixing processes is the draft (buoyancy). It creates pressure difference because of a difference in the density and weight of the flame gas vs. the outside air. The pressure at the bottom of a column of lighter weight gas is less than the pressure at the bottom of a column of heavier weight gas. The pressure inside of a TLUD, or any fire, filled with light weight hot gas is lower than the pressure of the cooler and heavier outside atmosphere. The secondary air follows this pressure gradient into the stove where it merges into and mixes with the pyrolysis gas.

**Flow Resistance:** If the flowing gas meets a resistance to its flow, the overall gas flow will be slowed and the overall pressure will increase. This will reduce the pressure gradient with the incoming air and so impede mixing. Too much flow resistance slows all flames, but can especially impede or extinguish flames turned down to a low-power level. Bluff bodies and concentrators increase flow resistance. Attention to flow resistance must be taken when designing a burner which places objects in the gas flow path.

**Forced secondary air:** Forced air creates pressure difference mechanically. A fan can create high pressure secondary air having an increased pressure gradient with the flame gas. Care must be taken with the design to get a smooth mix, and not disrupt the gas flows so much that uneven mixing occurs. A forced air stove will show improved performance if natural draft principles receive attention, working with the natural forces and not against them.

**The Venturi effect:**  Venturi mixers are not new. The Bunsen burner and carburetor are examples of Venturi mixers. Knowingly using Venturi mixing as a major mixing technique in TLUDs is new. Venturi mixing can function in a TLUD once the draft gets the pyrolysis gas moving. The pressure of the rising pyrolysis gas can then be altered in localized locations by placing an object in the flow path (see diagram below). Examples can be objects like a bluff body or a concentrator ring. The Venturi effect states that if the flowing gas accelerates its pressure drops, and if it slows its pressure increases. For a bluff body, the Venturi effect causes the gas pressure to rise at the impact point in the center, where the gas is slowed, and to be lowered around the edges where the gas is accelerated.

The question arises, is the Venturi effect in a TLUD strong enough to actually have an impact. The answer is yes, the impact is quite impressive and useful.

I (with help from Aprovecho) arrived at a Venturi bluff body burner design by looking at the pressures inside the TLUD stove, and noticing that the Venturi effect could be used to increase the pressure gradient between the pyrolysis gas and the secondary air. This could be used to rapidly drive the secondary air into the pyrolysis gas, improving mixing and combustion.

With an unobstructed pathway the gasses are subject only to forces which effect the overall flow, and the friction of the walls.

When an object is placed within the gas flow path, localized Venturi caused pressure changes are formed around the object. This is in addition to a slowing of the gas overall from flow resistance.

**Low**

**High**

The Venturi caused low pressure increases the pressure gradient with the secondary air, and the bluff body mixer utilizes this increased pressure gradient to drive secondary air into the pyrolysis gas, enhancing mixing.

**High**

**High**

Secondary Air

**Low**

1BLUFF BODY VENTURI MIXING

I hypothesize this toroidal flow to explain why the flame is not turbulent above the bluff body.

Toroidal flow

The natural draft TLUD bluff body mixing concept makes pressure gradient mixing, specifically Venturi mixing, the dominant mixing force. The pyrolysis gas exits the fuel chamber through a concentrator, then immediately encounters a bluff body and accelerates around it. With adequate draft, the gas can achieve substantial acceleration, considerably lowering its pressure at the edge of the bluff body by the Venturi effect. This lower pressure increases the pressure gradient between the gas and the secondary air. If the secondary air is introduced at this point, it follows the increased pressure gradient into the pyrolysis gas, creating a very rapid and thorough mix. There is no need to wait for turbulence or diffusion to mix the gasses. This is all with natural draft secondary air, and adds to the pressure gradient created by the draft. Because of its mixing speed it requires secondary air faster than most TLUDs, requiring a large secondary air entrance.

Of the several Venturi mixer designs which I have tried, the bluff body design has worked the best for minimal particulates and over a range of power levels.

**DOUBLE BLUFF BODY MIXER/BURNER:**

Intended to crack and burn the tars, this design has two bluff bodies and three concentrator rings, stacked one above the other; ring, bluff body, ring, bluff body, ring. The gas exits the fuel chamber through the first concentrator. The lower bluff body then rapidly mixes secondary air with the pyrolysis gas, rapidly burning the easy to burn flammable gasses (H2, CO, CH4). The heat from this combustion is concentrated by the second concentrator, creating a heat reservoir through which the hard to burn tars must pass. This creates the perfect conditions to crack them into short chain flammable gasses. These newly cracked flammable gasses are rapidly burned at the second bluff body burner, and any leftover tars have time and heat to crack and burn. The overall burn is very efficient. This process is shown in the following two diagrams.

TIME: Concentrated heat from the easy to burn gasses has time to crack the long chain hydrocarbons and carbon particles.

Wood gas

Air

Rapid mixing

Heat

Air

Rapid mixing

TIME: The newly cracked hydrocarbon gasses and carbon particulates have oxygen and time to burn

Completed burn

Wood gas is a dirty gas containing long chain hydrocarbons, carbon particles, and ash as well as easy to burn gasses. This flow chart shows a simplification of a way too cleanly burn wood gas in a TLUD-ND so that the only particulate emission is nonflammable ash.

Cooking vessel

**Double Bluff Body Burner**

Pot stand

Hot pyrolysis gas rising

Secondary air

Low pressure area where the easy to burn gasses (CO, H2, CH4) are rapidly burned

Newly cracked hydrocarbon gasses are burned giving very clean combustion

Cone shaped bluff body

Cone shaped bluff body

Secondary air

Fuel Reactor Chamber where the pyrolysis gas is generated. Pyrolysis gas is complex, with gasses, vapors, liquids, and solids, and is fairly difficult to burn cleanly. As shown above, we have a way of cracking and burning the tars effectively.

Heat from burning the easy to burn gasses is concentrated to crack the tars

This ring works better below the bluff body, I think because of the increased velocity of the gasses.

Typical 4” to 7” The bluff bodies should be about the same diameter as the fuel chamber.

This burner may be too tall for a cook stove, but might be excellent for other applications, such as burners for a large-scale power plant. This very efficient natural draft burner can burn an excessive amount of pyrolysis gas as created by forced primary air. As the amount of gas increases, its velocity increases, its Venturi pressure is lower, the pressure gradient increases, and more secondary air enters the gas flow. Thus, more gas means more secondary air, and less gas means less secondary air. The secondary air adjustment is automatic and proportional, not the backward pressure gradient as shown above. This enables the natural draft burner’s ability to keep up with the excessive high gas volume created by forced primary air.

For the double bluff body, I have not seen excess air as being a problem at the lower bluff body, but at the upper bluff body too much air can be a problem, causing soot.

**POSSIBLY FURTHER ENHANCING THE NATURAL DRAFT PRESSURE GRADIENT:**

My experiments show that the pressure where the gasses impact the concentrator ring or bluff body can increase above atmospheric pressure. This increased pressure could be used to further increase the pressure gradient over atmospheric pressure.

**Some thoughts about the Venturi bluff body/atmospheric pressure gradient:**

* The actual Venturi pressure around edge of the bluff body cannot be measured directly as this is a combination of the Venturi pressure and atmospheric pressure.
* The pyrolysis gas accelerates all around the bluff body, producing an increased Venturi gas/air pressure gradient, a very large gas/air surface contact, and a shallow depth for the air to penetrate into the gas, in what could be called a rounded vase shape.
* The Venturi/atmospheric pressure gradient cannot be diminished by using it up. As long as the secondary system provides open access to the atmosphere, the virtually infinite atmospheric pressure will continuously replenish the pressure gradient. If the secondary system restricts access to the atmosphere, the pressure gradient can be reduced via flow resistance. The lower bluff body of a double bluff body burner receives unrestricted secondary air, but the upper bluff body receives restricted secondary air.

High pressure area where the secondary air slows and impacts the ring.

Low pressure area where the pyrolysis gas accelerates

Increased pressure gradient from ‘increased-too-decreased’ pressure areas. Since the air is moving slowly and the mixing is fast, extra secondary air would be needed to keep pace.

Gas Air

**SINGLE ENHANCED BLUFF BODY MIXER/BURNER:**

Shorter stoves have less draft, and using a single bluff body in a shorter stove will cause a lazy and low efficiency flame. An enhanced bluff body can overcome this problem (see drawings below). It draws in secondary air through almost vertical tubes (the prototype uses 6 tubes) which are heated from the outside by the passing pyrolysis gas. The air inside the tubes is heated and initiates a draft inside the tubes, causing a flow of air up through the tubes. This preheated air is directed toward the thin curtain of pyrolysis gas from inside the bluff body, adding to the secondary air from the outside. Air entering the pyrolysis gas curtain from both the inside and outside increases the surface contact, and reduces the depth of penetrate into the pyrolysis gas. Very rapid mixing and burning ensues, allowing shorter stoves to use the very rapid Venturi pressure gradient mixing technique. The enhanced single bluff body is located in the same location as the lower bluff body in the double bluff body stove.

The secondary air aggressively pushes into the reduced pressure pyrolysis gas.

Low pressure area at the edge of the bluff body

ENHANCED BLUFF BODY

BASIC BLUFF BODY

Fuel Chamber

Hot pyrolysis gas

Fuel Chamber

Heat transfer from the hot gas to the secondary air produces draft inside the tubes.

With good draft, a simple conical bluff body accelerates the pyrolysis gas around the edges, decreasing its pressure. It needs adequate draft or the flame will be slow and lazy.

An enhanced bluff body with almost vertical tubes for secondary air helps mixing in short, low draft TLUDs. Tests show a very hot, fast, and short flame, even for a shorter stove with moderate draft. This hot flame helps increase the draft.

To help describe the capability of Bluff Body Venturi Mixing, I present below some hypothetical comparisons between mixing types, the bluff body mixer described above which lowers the pyrolysis gas pressure, an air stream system which lowers the secondary air pressure, and turbulence mixing which nullifies the pressure gradient.

**Comparing Venturi Pressures:**

**Air Stream mixing vs. Bluff Body mixing**

The TLUD mixing system shown below accelerates the secondary air into streams, hopefully reaching the center of the stove. This system is very good at providing surface contact, assuming the streams reach the center and gas does not leak up between the holes. The largest possible surface contact would be the circular area of the fuel reactor chamber. Depth of penetration is large, the radius of the chamber. Since the secondary air is accelerated into streams, it is the secondary air that experiences Venturi caused low pressure, not the pyrolysis gas like in a bluff body system. This arrangement would be efficient within its design range, but might have problems with turn-down or substantially increased power levels.

Atmospheric air pressure

Zero gradient

.002” water column

Bluff body edge gas pressure

.002” water column

.002” water column

Pyrolysis gas pressure

Secondary air streams pressure

Pyrolysis gas pressure

Atmospheric air pressure

**Air stream mixing:** Lowering the air pressure from atmospheric to stream pressure requires the air stream pressure to pass the pyrolysis gas pressure, dropping the gradient to zero before enlarging again. Final pressure Gradient = .002” water column

Comparing this secondary air stream mixing technique with bluff body mixing reveals some interesting pressure activity. As always, the pyrolysis gas begins at a lower pressure than atmospheric air due to the draft (buoyancy). The below hypothetical model (intended to show the principle only) assumes an equal amount of Venturi pressure drop (.004” water column) for both pyrolysis gas and secondary air streams. It shows that lowering the gas pressure gives more pressure gradient for mixing than lowering the air pressure. This is one of the reasons the bluff body mixer works exceptionally well, along with its’ very large surface contact and very shallow depth of penetration.

**Bluff body mixing:** Lowering the pyrolysis gas pressure with the bluff body, the pressure gradient begins increasing immediately. Final pressure Gradient = .006” water column.

More pressure gradient is available to merge and blend the gasses, like fan forced secondary air but better, being more evenly mixed.

**BLUFF BODY MIXER VS. TURBULENCE**

The pressure gradient makes the difference

The case for turbulence mixing, why it works:

**Strengths:**

Large surface contact

Shallow depth of penetration

**Weaknesses:**

No pressure gradient

Large potential for uneven distribution

Takes time and space to mix

The case for Venturi bluff body mixing, why it excels:

**Strengths:**

Large surface contact

Shallow depth of penetration

Increased pressure gradient

Automatic gas/air ratio adjustment

**Weaknesses:**

Double bluff body may be too tall for cooking stoves.

Secondary air

Pyrolysis gas

TURBULATOR

**-Lots of surface contact**

**-Shallow depth of penetration**

**-No pressure gradient**

**-Potential uneven distribution**

Shallow penetration depth

Large surface area

Permeability

Pyrolysis gas

Secondary air

Large pressure gradient

Bluff body Venturi mixing is something like Just-In-Time manufacturing. Everything needed for complete mixing arrives at the mixing point at the same time; gas, air, large surface contact, shallow depth of penetration, and increased pressure gradient.

Just-In-Time manufacturing allows the assembly to take place quickly and for the product to continue on to the next step. Bluff body Venturi mixing allows the gas and air to mix and burn quickly, then continue up to the next burner or cooking vessel.

**A Brief History of the Flame Spreader**

The bluff body burner is not a new way of burning. There is historical precedence for its use. What is new is its application to the TLUD cooking stove. The bluff body has been called by several names, flame spreader, flame plate, and dispersion plate, among them.

Its first recorded use is from 1857 when a flame spreading device was attached to the wick of a coal oil lamp. These flame spreaders had the solid plate on top with perforated metal sides, a technique still used in many stoves today. The TLUD bluff body uses only the plate.



Several flame spreaders of the type used in the nineteenth century.

A nineteenth century wick burner with a flame spreader at the top. The wick is immersed into the liquid gas (not pressurized) and wicks the liquid fuel up to the burner where flame heat vaporizes and burns it.



Designs using pressurized liquid gas and flame spreaders were used in WW2 by USA, British, French, and German field stoves. The designs heated the liquid gas, vaporizing it, and directed a stream of gas vapor at the flame spreader plate. As it spread out, the vapor ignited, forming a very efficient flame.

A World War 2 circa 1942 U.S. stove with flame spread by the flame spreader. A heat conductive metal like brass was used for the plate because it conducted heat to its center where the stream of gas vapor would hit it and be preheated to improve combustion.



Close-up of a WW2 German flame spreader plate.

My first designs used tubes crossing the gas flow path, fed with secondary air, and with slits running their length. The idea was that the pyrolysis gas flowing around the tubes would accelerate and decrease in pressure, causing air to rapidly exit the slits and mix with the gas. The design was successfully tested at both Aprovecho and Lawrence Berkley National Labs Burn Lab, but had too many parts, was too temperamental, and too fragile to be used commercially. The tubes created too much flow resistance, and so higher power levels had a deficit of secondary air and the stoves would smoke when turned up.

For several years after that my efforts met with only marginal success. Then a colleague described to me an experiment he had done where he directed a stream of flame toward a bluff body, and it seemed to help his stove burn cleaner. I studied this idea, saw that the gas pressure decreased around the edges of the bluff body, improving mixing, and adapted it to the TLUD stove. It worked, and was simple enough to be easily manufactured commercially. The design also made it possible for higher power levels to have plenty of secondary air, and to burn without smoke.

At one time I owned a World War 2 stove as shown in the above photo, and became familiar with the flame spreader principle by watching it operate. It seems that in the end, I was only adapting an old idea to a new situation in the bluff body TLUD burner. Since the TLUD is a gas stove, like the WW2 stoves, it makes sense that the flame spreader idea would work.

**A comparison of the WW2 stove and the bluff body TLUD stove**

Pumping up the pressure in the liquid gas stove allows a very high velocity stream of vapor. This will increase the pressure gradient and surface contact with the air, and provide a shallow depth of penetration, excellent for mixing.

The TLUD cannot achieve the same high velocity and very low vapor pressure as the pressurized stoves, and so the technique must be adapted accordingly.

Very high velocity and low pressure

Very high pressure

moderate velocity pyrolysis gas

Below atmospheric pressure

Heat from the flame vaporizes the liquid gas.

Wide opening and cone shape plate reduces flow resistance for the TLUD.