TESTING & MODELING THE WOOD-GAS TURBO STOVE

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ABSTRACT

Through the millennia wood stoves for cooking have been notoriously inefficient, unhealthy and slow.

A new "wood-gas" cook stove has been developed that has >30% thermal efficiency, can be started, operated and stopped with very low emissions and can use a wide variety of biomass fuels. This "Turbo Stove" operates with 3 W of blower power or other air supply to produce 1-3 $kW_{thermal}$ for cooking. It is simple and inexpensive to build.

Data is presented for this stove on a wide variety of fuels. The stove will bring a liter of water to boil in 4-10 minutes and can be turned down to the simmer level for longer cooking and increased efficiency.

The stove operates in several different gasification and combustion modes. In the "volatile burning" mode, the stove makes 18-25% charcoal from biomass fuels. In the "charcoal burning mode" the charcoal is gasified to produce a CO flame. If longer cooking is required, additional fuel can be fed from above, but other modes require more operator skill.

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For a new stove to be accepted it must fit the fuel supply, cooking practices , construction methods and commercial infrastructure of each country. Therefore, it must be possible to make a variety of stoves and requires understanding of the basic mechanisms of gasification and combustion of "wood-gas". A model of the wood-gas "Turbo Stove" is described based on the measured parameters in this paper.

INTRODUCTION - WOOD COOKING VS WOOD-GAS COOKING

Since the beginning of civilization wood and biomass have been used for cooking. Still, today over 2 billion people cook badly on slow, inefficient wood stoves that waste wood, cause health problems and destroy our forests. Electricity, gas or kerosene are preferred for cooking - when they can be obtained However, they are costly, contribute to global warming, and depend on having a suitable infrastructure often not available in developing countries

In the last few decades, many improved wood stoves have been developed (the Chula, the Hiko, the Maendeleo, the Kuni Mbili, the Wendelbro, etc.[1] These new wood stoves are often more difficult to manufacture and they do not offer good control of cooking rate. They are often not accepted by the cooks for whom they are developed.

Since 1850 the preferred means of cooking has been first gas, then electricity. Gas is still preferred by many cooks. Electric cooking can be 60% electric-efficient, but power generation and distribution is typically 30% efficient, yielding an overall efficiency of 18% for electric cooking.

We have developed several simple, inexpensive wood-gas stoves which can bring the "joy of cooking with gas" to everyone while using a wide variety of renewable biomass fuels or coal.[2-4]

PRINCIPLES OF DOWNDRAFT GASIFICATION FOR COOKING

BIOMASS GASIFICATION

When biomass is burned with insufficient air in a gasifier, it makes a "producer gas" containing primarily CO, H_2, CO_2, H_2O and CH_4. Over a million gasifiers powered the civilian cars and trucks of Europe and Asia during WW II. Downdraft gasifiers are "tar-burning, char-making" and are most suitable for biomass which contains 80% volatile material. Updraft, "char-burning, tar-making", gasifiers are often used for coal which can be 80% char.

In conventional downdraft gasifiers, air passes **down** through the fuel mass, then in the flaming pyrolysis zone burns the volatiles and tars while making charcoal and pyrolysis gas. The charcoal then further reduces the CO_2 and H_2O combustion products back to CO and H_2 fuel.

THE "INVERTED DOWNDRAFT GASIFIER"

In **inverted** (top burning) **downdraft gasification** air passes up through the fuel and meets the flaming pyrolysis zone where the reaction generates charcoal and fuel gas as shown in Fig. 1.[2,3]

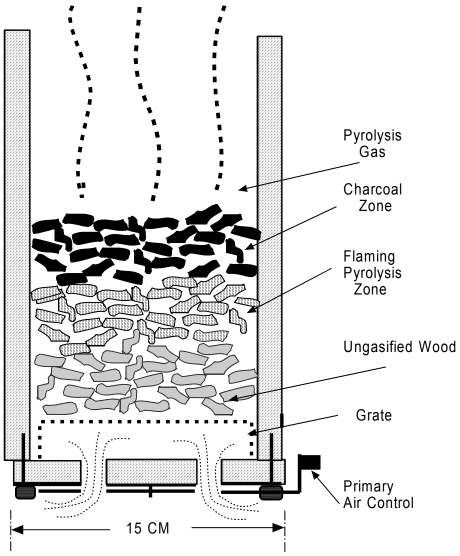


Fig. 1-Natural convection gasifier stove made with 15 cm riser sleeve[2,3]

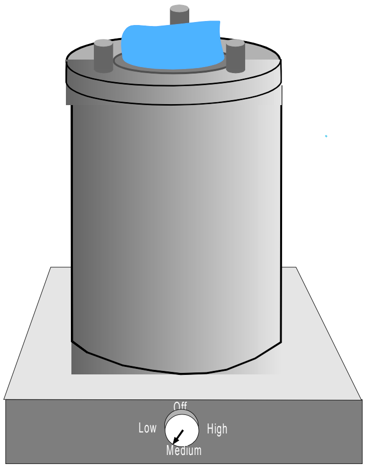


Fig. 2-Forced convection Turbo Stove with 3 kW flame from a 3 W blower[4]

NATURAL VS FORCED CONVECTION

Natural convection provides poor mixing of air with fuel gases and can result in incomplete combustion, soot and emissions in open wood stoves. A chimney can supply 1 mm water pressure per meter of height. Addition of a chimney for cooking can greatly improve wood combustion in closed models, but also adds complication and requires wasting heat to operate.

Forced convection provides good mixing and combustion for gas cooking and is widely used in homes and camping stoves. The 3 W blower used in the Turbo Stove provides 7.5 mm water pressure and makes clean cooking possible.

THE "TURBO STOVE"

The Community Power Corporation and the Biomass Energy Foundation have developed a new "Turbo wood-gas stove" using forced draft from a 3 Watt blower. One design is shown in Fig. 2. It consists of an inverted gasifier close coupled to a burner section to mix air and gas and burn cleanly. A 3 Watt blower generates ~ 7 mm water column pressure, equivalent to the draft of a 7 meter chimney. We have made it from an outer 1 gal paint can, an inner burner can and a fuel magazine or with many other construction methods.[4] Several burners can be assembled to make a cooking "range". An oven can be placed on one of the burners for oven heat.

The stove can be started and operated indoors with no exhaust fans and no odor of burning wood. We have taken the stove to India and the Philippines and cooked with the Turbo Stove in small villages and on conference room desks with no odor. While the Turbo Stove currently uses a 12 Volt 3 Watt blower, the power could come from stored compressed air, bellows, wind-up generators, photovoltaic, thermophotovoltaic, windup motors, thermoelectric or other sources.

CONSTUCTION AND OPERATING THE TURBO STOVE

THE RESEARCH TURBO STOVE

The research Turbo Stove shown in Fig. 3 consists of

- An inverted downdraft gasifier and fuel magazine
- A combustion section which burns the gas
- Supports for a pot
- Regulated air supply for gasification and combustion

as shown in Fig. 3. This permits independent adjustment of the air to the gasification section and the combustion section for optimizing cooking conditions at both high and low levels.

The rate of heating and boiling was used to measure the heat transfer for cooking. Draft meters were used to measure the

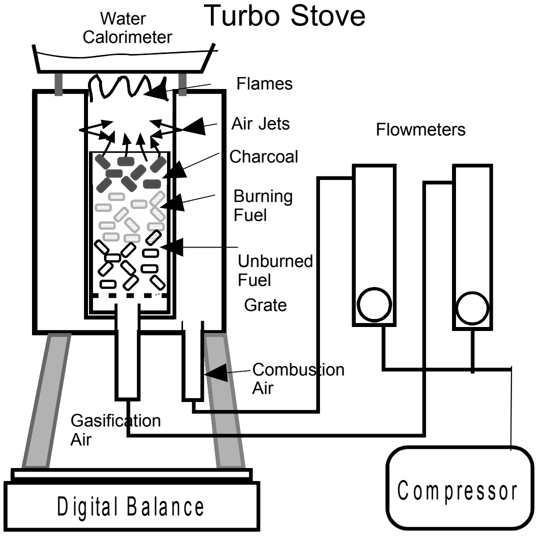


Fig. 3 - Research Turbo Stove, showing separate supplies for gasification and combustion air.

pressure drop for gasification and for combustion (typically 0.25-0.75 mmw for gasification and 2.5 mmw water pressure for combustion).

THE PROTOTYPE STOVE

Compressed air and flowmeters do not a practical stove make. We have also built the prototype stove shown in Fig. 2 that is easier to operate and less expensive. It permits adjusting the power level by adjusting the gasification air. Some of the data below were taken on the research and some on the prototype stove.

STARTING AND OPERATING THE STOVES

In a typical run, the stove is filled with weighed pellets of the dry fuel of choice. A layer of starting chips, (chips, charcoal, or other porous materials soaked in alcohol, fat or kerosene) is placed on top. The blower is turned on and the starter chips are lit with a match. For the first few minutes the starter chips ignite the fuel below and make a bed of charcoal that the gas must pass through. In 1-5 minutes, depending on the fuel, the main fuel mass is ignited and burns downward regularly in flaming pyrolysis mode until the reaction zone reaches the grate, making charcoal as it goes. The test variables are shown in Fig. 4 for the research stove and Fig. 5 for the prototype stove.

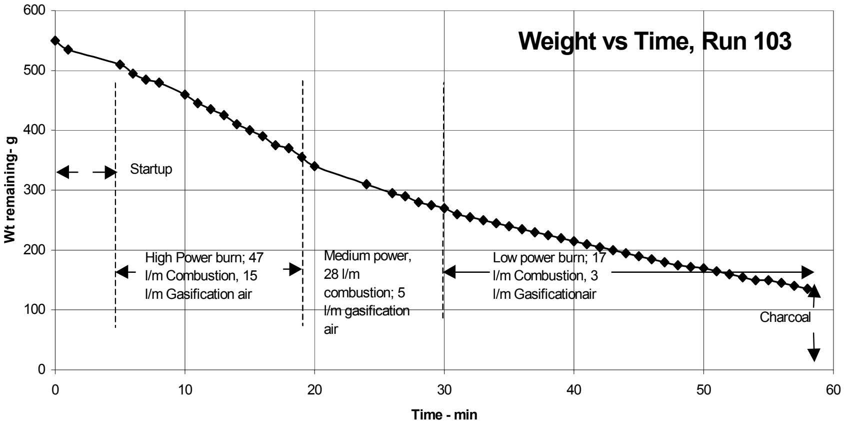
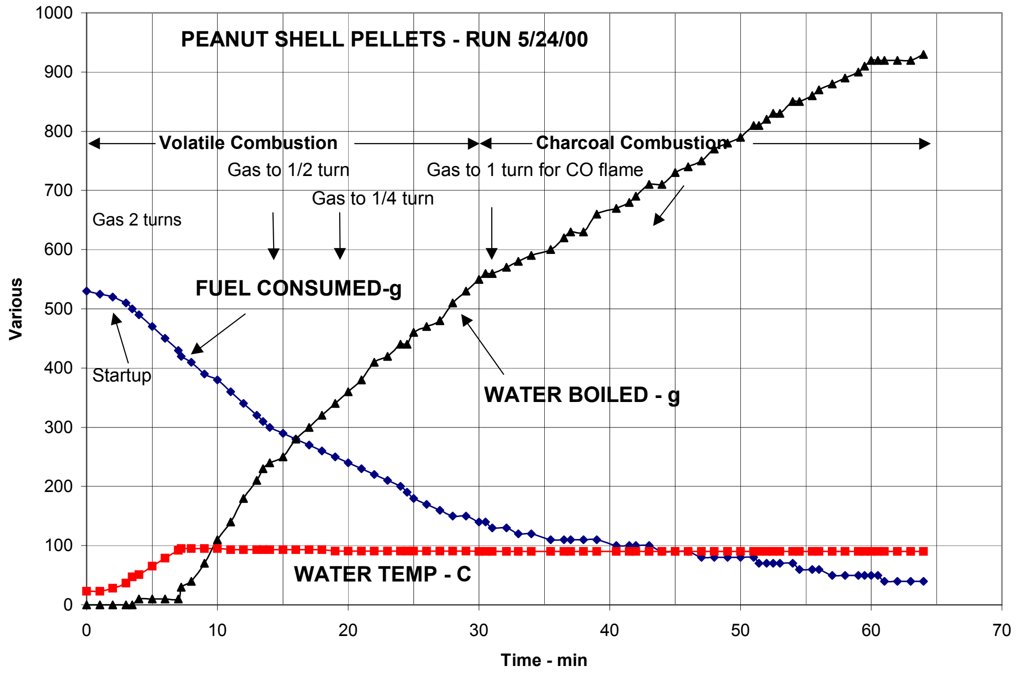


Fig. 4 – Typical operating data on the research Turbo Stove showing weight of fuel remaining vs time at high, medium and low power levels

Table 1 – Air Fuel Ratios for gasification and combustion, power levels, turndown and superficial velocity for research stove

	FUEL RATE	GASIF AIR	COMB-USTION AIR	GASIF AIR/ FUEL	COMB-USTION AIR/ FUEL	POWER	TURN-DOWN	SUP VEL
POWER	g/m	g/m	g/m			kW	P/Pmax	m/s
Maximum	11.3	18.0	56.6	1.59	5.01	2.83	1.00	0.062
Medium	7.1	6.0	34.0	0.84	4.79	1.78	0.63	0.028
Low	4.6	3.5	21.7	0.75	4.73	1.15	0.41	0.017



TEST PROCEDURE

In operation the Turbo Stove is operated on a balance and the loss of weight of fuel and water are recorded as test cooking progresses as shown in Figs. 4 and 5. The stages in cooking are shown in Table 2. In some cases the run is stopped after the flaming pyrolysis zone reaches the grate and the volatiles have been burned. However, at this point the charcoal begins to be gasified by the incoming air and cooking can continue until all the fuel is gone.

DATA ON THE TURBO STOVES

BEHAVIOR OF VARIOUS FUELS

A typical set of data for the research and prototype stove are shown in Figs 4 and 5 and data collected on these runs are shown in Tables 1 and 2.

The Turbo Stove has been satisfactorily operated on dozens of fuels. The behavior of six fuels tested more extensively is shown in Table 3. In addition to many biomass forms, coal was also found to be very a satisfactory fuel for the Turbo Stove.

Some of the tests done for this paper were made on "¼ inch" (6.2 mm) stove sawdust pellets, a readily available, high density, reproducible fuel except where otherwise noted. Table 1 and Fig 4 show data taken on stove pellet fuel made from sawdust. Pellets are widely marketed for pellet heating stoves in the U.S. for $2.50 for a 20 kg bag. This would be sufficient to cook 40 typical meals. Figure 5 and Table 2 were made using peanut shell pellets, a potentially good fuel wherever peanuts are produced.

FUEL CONSUMPTION RATE AND COOKING POWER

The fuel consumption rate is a direct measure of cooking power, provided all the gas is subsequently burned in the burner section. The heating value of most biomass with 5-10% moisture (Denver dry) is ~18 kJ/g. The stove typically produces 20-25% charcoal after the volatiles have been burned. The charcoal typically has a higher heating value of ~24 kJ/g. In the tables the power level is calculated from these values. A gasification rate of 10 g/m gives 2.5 kW, comparable to the large burner on modern gas or electric stoves.

TURNDOWN RATIO

An important criteria for successful stove cooking is the "turndown ratio" of the stove. Initially the stove should develop high power to bring water or oils to cooking temperature. After cooking temperature is reached it is desirable to turn the power level down to just maintain that temperature. The turndown ratios for wood and peanut shell pellets are shown in Tables 1 and 2.

Table 2 –Stages in test of peanut shell pellets (Fig. 4), showing flame intensity, water evaporated, turndown and efficiency at various stages of heating water

TIME	CONDITION	GASIFICATION AIR	FUEL REM	WATER LOST	HEAT USED	HEAT TO POT	EFFICIENCY	FLAME INTENSITY	TURN-DOWN
min		**Turns**	**g**	**g**	**kJ**	**kJ**		**kW**	
0.0	Startup	2	530	0					
1.0	Pot on flame	2	520		3300	909	28%	4.1	100%
7.2	Rocking Boil	2	420						
13.5	Turn Down	1/2	310	230					
↓	Medium				1050	253	24%	3.2	78%
19.0	Turn down	1/4	240	340					
↓	Low				1650	506	31%	2.3	56%
31.0	Only charcoal left	1	130	560					
↓					2160	851	39%	1.1	28%
64.0	Off	1	40	930					
	SUMMARY	NA	490	930	8160	2518	31%	2.1	31%

It is desirable to be able to operate at lower power levels than maximum and a major advantage of the Turbo Stove is that it can be operated at lower powers reducing the air for gasification and burning less gas. For most biomass the energy content is 18 kJ/g for fuel with about 10% moisture. In the volatile burning mode the volatile energy content is about 15 kJ/g, while the 25% charcoal contains 24 kJ/g. Calculations included here have been made on this basis.

BOILING EFFICIENCY

There has been entirely too much emphasis placed on “cooking efficiency”, but it is certainly one importuned factor in evaluating stoves. Equally important is low emissions, high intensity and good turndown ratio.

The data shown in Table 3 for boiling efficiency was calculated from the ratio of energy used for boiling water (in an 18 cm diameter pot filled with 1liter of water) to the fuel consumed after the water reached the boiling point until the end of volatile burning. It typically ranges from -40%, depending on fuel, length of boiling time, pot size and other factors.

Table 3 – Operating and derived data for runs on selected fuels

TEST FUEL [1]	**PEANUT SHELL PELLETS**	**WOOD PELLETS**	**COCO-NUT SHELL**	**PALM NUT SHELL**	**WOOD CHIPS**	**COAL**
Test Date	5/25	5/9	4/22	4/27	4/26	4/28
FUEL DATA						
Moisture Content [2]	6.4	6.5	6.2	6	7.8	3.1
Fuel Wt. –g	500	500	305	150	180	260
Fuel Density-g/cm^3 (3)	0.58	0.64	0.48	0.26	0.265	1.69
RUN DATA						
Volatile burn time-min	30	41	19	13	15	37
Volatiles burned g	490	410	215	130	150	150
Time to Boil min	7.2	7.0	13.0	8	6.0	10.0
Charcoal yield - g	130	90.0	90.0	20	30.0	130.0
Water boiled - g	930	850.0	220.0	100	145.0	850.0
DERIVED DATA						
Charcoal Yield-%[4]	26	18	29	13	17	50
Boiling Efficiency [5]	31	31.8	37.5	33	20	24
Average Intensity [6]	2.1	2.5	2.8	2.5	2.5	2.4

Notes: (1) The peanut shell pellets were 3/8" diameter from Birdsong Peanuts, Georgia; the wood pellets are standard ¼ inch wood heat pellets from Ace Hardware; the coconut shells were obtained from the Philippines hammermilled to 1 com on an edge; the palm nut shells were obtained in Indonesia; the wood chips were mixed tree chips from Denver ~ 2 cm on an edge; the coal was bituminous from Denver crushed to 2 cm on an edge.

(2) Moisture in wt %, wet basis; (3) Apparent fuel density calculated from magazine dimensions and weight; (4) Charcoal yield calculated from char remaining at end of run and initial fuel weight; (5) Boiling efficiency calculated from fuel consumed during steady boil, based on 15 kJ/g for biomass volatiles, 35 kJ/g for coal volatiles; (6) based on 15 kJ/g for volatiles and burn time of volatiles.

EFFECT OF FUEL MOISTURE CONTENT

The fuel moisture content is recommended to be <20% (wet basis) for the operation of engines. However, we have found that fuels with up to 30% moisture can be used in the

Turbo Stove quite satisfactorily. We believe that this is because it is necessary for each layer of fuel to ignite the next lower layer. When the layer is dry, the fire propagates easily, but with wet fuel more charcoal is consumed to dry the layer before the reaction can proceed. This is born out by the fact that with bone dry fuel charcoal often exceeds 25%, but with 30% moisture fuel only 4% charcoal remained after the pyrolysis was complete.

AIR-FUEL RATIOS FOR GASIFICATION

The **air/fuel** ratio is a very important criterion for solid, liquid and gas fuels since there is only one theoretical value that produces maximum flame temperature and minimum emissions.

Table 1 shows the air/fuel ratio (based on the sum of gasification and combustion air) for three conditions, the maximum, medium and low output as 4.5-5.7. The theoretical value for “typical dry biomass is 6.3 but depends on fuel composition and moisture content.

The air/fuel ratio is an important parameter in the clean gasification and combustion of all fuels including biomass, charcoal and coal. The Air/fuel ratio was measured for wood pellets in the research stove and is shown in Table 1.

GAS HEATING VALUE

The gas heating value of raw producer gas containing significant condensable volatiles (tars) is difficult to measure, since measurements are usually made at room temperature after the tars have been removed. The gas higher heating value varies with the air/fuel ratio used for gasification and the superficial velocity. We are in the process of measuring it, but we expect is to vary in the range 5-7 MJ/Nm^3.

DIFFERENT MODES OF TURBO STOVE OPERATION

Cooking is typically a batch process and successful operation of the Turbo Stove requires the cook to estimate how long a particular task will require. If further cooking or water heating is required, there are several ways to extend the heating time.

On startup, the gasifier converts the biomass fuel volatiles to gas which is burned and leaves behind up to 30% charcoal which can be saved or burned for additional cooking. In the stove described in Table 3 times of 19-37 min were recorded for the various fuels.

After the volatiles have all been burned a dramatic change in the flame occurs and with the air then gasifies the charcoal to CO, giving a different flame and much hotter temperatures at the grate.

If even longer cooking is required, more fuel can be added judiciously in an “updraft” mode in which charcoal combustion supplies heat to pyrolyse the new fuel..

These other methods may require more operator skill and different design and construction.

SAFETY

Producer gas was the only gas fuel widely available until 1940 when natural gas pipelines became common. Since producer gas contains 10-30% CO, it is a real health hazard if the flame is extinguished or incomplete combustion occurs. (Smoky open fires and insufficient cooking fuel are also major health hazards in the world today.)

Therefore it is necessary to mandate good practice in using the Turbo Stove. In the volatile combustion mode CO is a minor hazard because if the flame should go out, the copious smoke warns the operator to re-ignite the fire or move the stove outside. However, in the charcoal combustion mode the CO is odorless and could pose a health hazard.

It is recommended that all stoves including the Turbo Stove should be operated under a hood carrying the cooking odors and possible stove emissions to the outside by natural or forced convection. That is the practice in most kitchens in developing countries today and should be followed as the rest of the world develops.

MODELING THE TURBO STOVE

TAYLORING THE STOVE FOR VARIOUS APPLICATIONS

For a new stove to be accepted it must fit the fuel supply, cooking practices, construction methods, size of servings and commercial infrastructure of each country. Therefore, it must be possible to make a variety of stoves and requires understanding of the basic mechanisms of gasification and combustion of "wood-gas". For this reason it is desirable to have a complete model of the wood-gas stove from which new designs can be constructed with a minimum of testing.

Optimization of stove behavior ultimately depends on reaching a maximum heat transfer to the cooking pot while minimizing emissions and soot. This is a multivariable problem and must be broken down into its component parts for solution.

SUPERFICIAL VELOCITY

The superficial velocity (SV) is defined as "gas production rate/cross section" and is measured in m/s, btu/ft2-hr, etc. It is an important figure of merit of gasifiers and combustors. Each device will have a maximum SV that it can operate at satisfactorily. In downdraft gasification the SV determines the intensity of the flaming pyrolysis reaction and so controls gas, charcoal and tar production. The World War II gasifiers typically operated at 0.1-1.0 m/s to produce low tar gas and consume most of the charcoal.[5]

The Turbo Stove operates in the range 0 to 0.06 gasification superficial velocity because at higher gas rates the charcoal is blown out of the top of the gasifier. The SV for three conditions are shown in Table 1 for the research gasifier operating on wood pellets.

ESTABLISHING STOVE CRITERIA

To model the stove it is necessary to define the application in terms of maximum power required, minimum burn time at full power and whether charcoal is desired as a by-product.

THE GASIFICATION SECTION OF THE TURBO STOVE

The gasification section is relatively simple to model as shown in Table 4. From the burn time at full power one first calculates the fuel requirement, using 18 kJ/g for volatiles, 24kJ/g for the charcoal or 21 kJ/g for the fuel (adjusted to the moisture and ash content). The maximum power required determines the rate of production of gas, the air/fuel ratio determines the gasification air that must be supplied and the superficial velocity determines the diameter of the gasifier chamber.

In Table 4 the fuel magazine diameter and height for a hypothetical 12 kW gasifier required to burn for 2 hours for community cooking are derived. We look forward to building it.

THE COMBUSTION SECTION

The combustion section of the stove is less easy to model, since it depends on the mixing of the combustion air with the rising gases. Many combustion devices are rated in terms of "combustion Intensity", which can range from 10^3 to 10^9kJ/h-m^3 for devices ranging from ovens to special burners.[6]

The combustion zone in the Turbo Stove measures 10 cm diameter X 6 cm tall with a multitude of small holes for air injection. At a power level of 2.5 kW, the combustion intensity is ~3 kJ/h-m^3, moderately high. We find that at power levels above 2.5 kW the flame rises above the burner and may blacken the pot due to incomplete combustion. We believe that the combustion chamber for other Turbo Stoves should have the same combustion intensity, but not necessarily the same diameter as the gasification section.

SUMMARY

We have measured many important gasification and combustion properties of biomass gas made in the Turbo Stove and believe that this stove could solve many problems in world cooking. We present here a simple model for sizing other stoves.

Table 4 – Hypothetical model of gasification section of a 12 kW_{th} Turbo Stove designed to burn 2 hours at 12 kW_{th}

INPUT REQUIREMENTS:		**Source**
Maximum Power – kW_{th}	12	Assumed
Cooking time @ Pmax - hr	2	Assumed
Charcoal (Yes/no)	no	Assumed
FUEL PROPERTIES		
Fuel	**Coconut Shells**	**Assumed**
HHV (dry) kJ/g	21.0	Typical biomass, ash free, dry
Fuel Moisture Content %	6.0%	Denver dry
Ash Content - %	0.7%	Measured
Adjusted fuel HHV - kJ/g	19.6	Calculated
Density - kg/l	0.48	Measured
GASIFIER REQUIREMENTS		
Fuel Rate - g/s	0.61	kJ/s÷kJ/g
Fuel consumed in time-g	4408	Run timeXfuel rate
Air/Fuel Ratio	1.60	
Gas Produced - g/s	1.59	(1+A/F)XFuel rate
Molecular Wt - M(g)	25	Assumed
Gas Produced - Nm3/s	0.00143	(22.4 l/mole)XM(g)X10^{-3}/M
Maximum SV - m/s	0.06	Measured
Gasifier area - m2	0.0238	m^3/s÷m/s = m2
Gasifier diameter - cm	**17.4**	D = $(4*area/pi)^{1/2}$
Fuel volume - cm3	9183	Weight/density
Fuel magazine height-cm	**38.6**	Volume/area

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