

Operation and modelling of an updraft long-stick wood gasifier

A. Saravanakumar and T.M. Haridasan

*Department of Bio-Energy, School of Energy, Environment and Natural Resources
Madurai Kamaraj University, Madurai, Tamil Nadu 625 021, India
E-mail (Saravanakumar): sara_mnes@yahoo.co.in*

Thomas B. Reed

Biomass Energy Foundation, 1810 Smith Road, Golden, CO 80401, USA

R. Kasturi Bai

*Department of Bio-Energy, School of Energy, Environment and Natural Resources
Madurai Kamaraj University, Madurai, Tamil Nadu 625 021, India*

Even though biomass gasification technology has come up in the past with impressive applications, the exact details of the gasification process are yet to be completely understood quantitatively. On the basis of the experience of gasifier users with regard to the efforts and energy needed for wood chip preparation in a typical gasifier, we have embarked on the development of a gasifier suitable to work with long-stick woody biomass as the feed material to avoid major fuel preparation problems in rural settings.

With this concept, a 25m³/hr capacity updraft gasifier was designed and constructed. Since the interest here is in exploring and validating this concept, an updraft gasifier was designed. This gasifier attains a high-energy release rate per unit area due to high inlet air velocity and activated reaction in the combustion zone. The temperature ranged from 922° C in the combustion zone to 128° C in the drying zone. In all the zones, the heat balance equations show a good fit between the theoretical and experimental values. The gasifier was operated in a batch mode, both bottom-lit (conventional) and top-lit, and the air flow and gas outflow were measured. The temperature of the raw gas was measured. The gas and air flows can be converted to the air/fuel ratio (A/F), the most important aspect of gasifier operation. A/F shows operation in a combustion mode at start-up, a gasification mode for the middle part of the run and a charcoal gasification mode at the end of the run.

For modelling, the gasifier was divided into a drying zone, a pyrolysis zone, a combustion zone and a reduction zone.

1. Introduction

Wood was the primary energy source for cooking, heating and metal production from the beginning of recorded history until the time of the industrial revolution. At the end of the middle ages, wood was used across India in smelters producing iron, copper, lead and other materials. Industrialization continued and demand grew for these products. The demand for wood exceeded the availability, causing the shutdown of many smelters, shortages of wood for cooking, and deforestation. Wood chips are one of the sources of biomass renewable energy that can produce gas through gasification. This source has the greatest potential of any renewable energy option for base-load electric power production for electricity generation and heating. High penetration of biomass technologies requires an abundant supply of biomass resources. Wood shavings in fine form from wood process industries and agricultural wastes have also been used to augment the

supply of heat both in domestic and industrial situations. Hislop and Hall [1996] reported that in the Third World, where the availability of industrial electricity is seen as a key factor in assisting development in rural areas, gasification can provide a local source of electricity using local woody biomass. The primary research in wood gasification for many years was in the area of design and performance aspects of gasifiers, where tar minimization has been the primary concern. The issues of feedstock preparation for wood as an energy source were of meagre interest. As a result, research in coal gasification has progressed much further than research in wood gasification.

The use of long-stick wood for gasification is unique in that there is a wide range of fuel sizes and moisture contents available and underutilized. The major problem of the handling and preparation of input in the form of wood chips still remains a noticeable stumbling-block in the penetration of this technology both in industries and

in the domestic sector. This situation is more serious if we have to install gasifier systems in remote rural areas, where they are really needed. These are the regions mostly suffering from shortage or total absence of power. Such power is initially needed for blower operations and also for wood cutting. Feedstock preparation is thus an important aspect of the total system planning and such preparation typically involves cutting wood into pieces of the required size. Electrical power, human power, and the storage facility involved in such processes make their functioning cumbersome, especially in remote areas. For example, the chip size recommended by the manufacturers of the gasifier feed system must be ascertained before obtaining wood chips from a supplier, or before acquiring any chipping or shredding equipment. Miles [1992] brings out the emphasis laid in the report of the International Energy Agency Biomass Thermal Gasification Activity in which the gasification technology has constraints of feed preparation for wood-based systems and the need for special designs for loose biomass as feed are highlighted.

The cutting of wood involves a sizable proportion (above 10 % and up to 15 %) of wood wasted as dust. Sawing alone generates 10 % sawdust on weight basis. Where the cost of wood is high, this wastage will be a major cost addition. For example, if a tonne (t) of wood costs around US\$ 26, the price now prevalent in India, then the wastage cost is at least around US\$ 3/t. Additional cost caused by loss of moisture from 30 % to 15 % (and hence reduction in weight) of the wood will result if the fuel is left to dry for just a few days after it is cut into small pieces. This further adds to the cost. Wood chips suitable for medium-size gasifier reactors are made available now by manual cutting. Mechanical cutters, electrical cutters, briquettes, and charcoaling can control the dimensions. However, the above methods of preparation of wood chips have disadvantages such as consumption of electricity, high human labour needs, dust collection, enormous noise production, and occasional unexpected accidents during processing. Therefore, it is not possible to process and store the wood for a long period. Hence, to alleviate these problems, one alternative is to focus on long sticks as the feed material in the gasifier. In the spirit of using an energy plantation for such a gasifier system, it is preferable to use such sticks from the branches of trees, which can be replenished at the plantation site within a shorter time span as compared to big trees being cut.

2. Old and new updraft gasifiers

Experimental studies [Bamford et al., 1946; Tran and White, 1992] yield temperature as a function of time within the wood under packed bed combustion conditions. Most earlier studies on updraft gasifiers were confined to small wood pieces as feed. For example, Khummongkol and Arunlaksadamrong [1990] have studied an updraft gasifier with sun-dried mangrove wood of size 2-5 cm long and about 5 cm in diameter. Bhattacharya et al. [1999] worked with two-stage gasification using wood chips shaped like cubes with sides in the range 10-15 mm,

dried by a solar dryer. On the other hand, Bryden and Ragland [1996] have studied the whole tree by utilizing a deep, fixed-bed combustor/gasifier. Wood logs 20 cm in diameter were smouldered in a 3.7 m deep fuel-bed. However, Kayal et al. [1994] used an updraft gasifier with bundles of long jute sticks (15 cm long and 1 cm outer diameter).

Saravanakumar and Haridasan [2002] in their studies observed that wood logs could be pyrolysed in the temperature range of about 275-325° C. The ratio of volume loss of wood per second to volume of the wood used is found to be 0.0015, indicating the long-range feasibility of adopting this method. From this experiment, they have also learnt that controlled pyrolysis of wood is a desirable strategy. The loss of wood in the process is negligible. The time for fuel-wood preparation is short.

Conventional updraft gasification has the advantage that it can burn very wet wood and converts all of the biomass to combustible gas. It has the disadvantages that the gas can contain up to 20 % volatiles from the wood, and so is unsuitable for operation of engines.

A new form of updraft gasifier, the “top-lit updraft gasifier” (also called the “inverted downdraft gasifier”), was developed in 1991 [Reed, 1991]. If the reaction takes place at the top of the fuel charge, the volatiles are burned by the incoming air from the bottom, forming a bed of charcoal on top of the fuel. These gases then pass through the charcoal, resulting in tar levels from 100-2000 ppm, depending on the superficial velocity of the gases [Reed et al., 1999; 2001]. Because the reaction moves counter-current to the air, the fuel-bed is burned at the same rate as the reaction moves against the fuel. The top-lit updraft gasifier is now being widely used for cooking and power generation. With dry wood it can also produce more than 20 % of a good grade of charcoal.

Top- and bottom-lit gasifiers are fundamentally very different. The bottom-lit gasifier is a “char-burning, tar-making” gasifier, while the top-lit gasifier is a “tar-burning, charcoal-making” gasifier. Both forms of gasifier have been tested and are discussed in this paper.

3. Design of gasifier

On the basis of the ideas developed from the preliminary work, a long-stick wood gasifier for updraft mode was constructed for both the bottom- and top-lit operations. A schematic diagram of the set-up is given in Figure 1.

The gasifier in Figure 1 was designed and constructed using mild steel sheet with 4.3 mm thickness and a volume of 0.714 m³. It is square in cross-section. The total height of the gasifier is 1.34 m. The internal length of the gasifier is 75 cm. The hopper is the primary storage area for the fuel-wood. The feedstock, long-stick wood of length 68 cm and thickness 6 cm, is placed in the top of the hopper through the inlet. The hopper is designed in such a way that it is able to hold wood that can produce the gas continuously for 5 to 6 hours in a batch process. The wood sticks had a typical moisture content of 25 %. The energy content of the wood was 20 MJ/m³ on a dry basis.

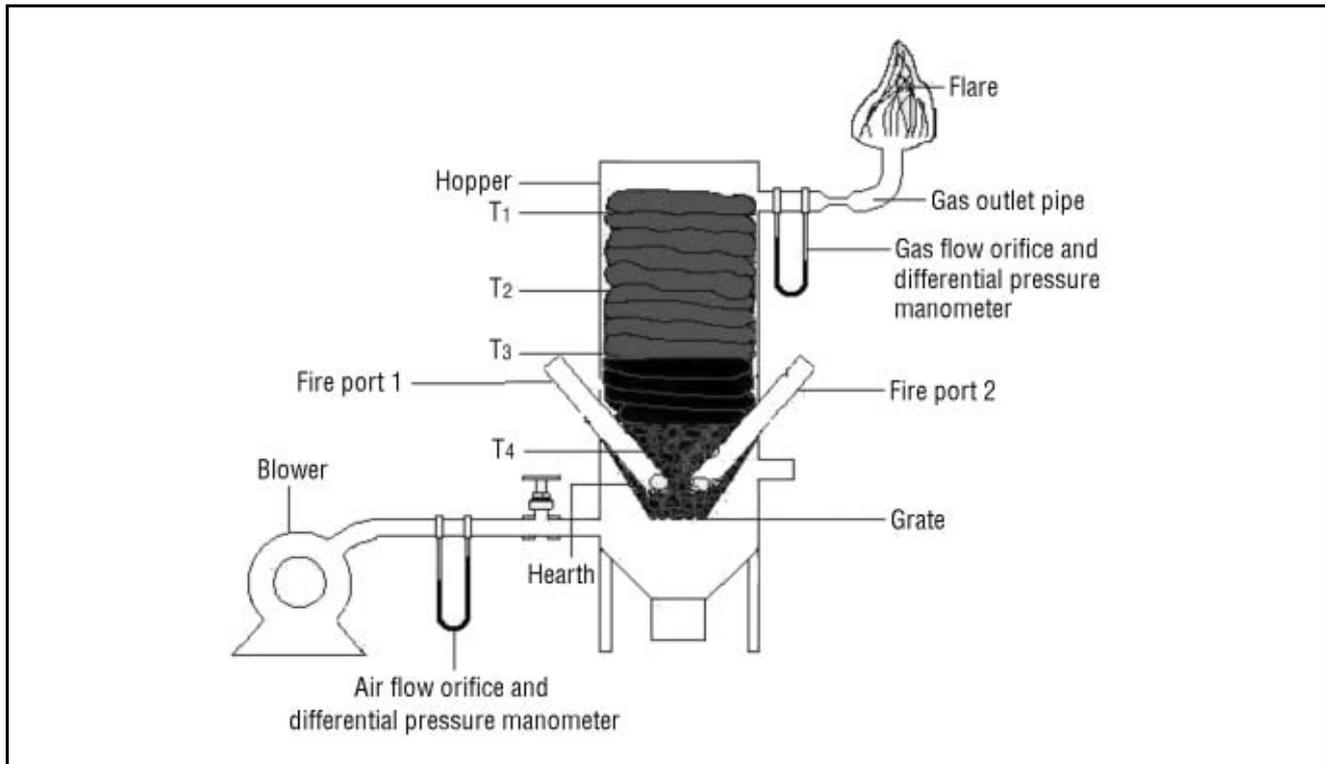


Figure 1. Schematic view of bottom-lit updraft long-stick wood gasifier

4. Operation of gasifiers

4.1. Bottom-lit operation

Initially, charcoal pieces are first loaded up to air nozzle height. Then long-stick wood is packed up to the full capacity of the hopper. The moisture content of the wood was typically 25 %. The hearth is made up of castable cement to resist higher temperatures up to 1600° C with a mild steel exterior cladding. The air from the blower for partial combustion enters the hearth through an air nozzle. The air nozzle tube is made up of stainless steel (SS) material of 3.8 cm diameter. There are two air nozzles fixed on opposite sides of the hearth. The positioning of the grate below the hearth zone in the gasifier helps the reduction reactions. The grate directly supports the combustion zone and must be capable of letting ash fall through without excessive loss of fuel. In addition, the grate is used to control reactor pressure drop and hence to maintain the gas production rate. The long-stick wood is packed into the hopper in a horizontal position. Air is supplied to the gasifier using an electric blower with a control valve capable of supplying the necessary air at constant speed. Air enters below the combustion zone and the producer gas leaves near the top of the gasifier. Air and gas flows are measured with an orifice and differential manometer, as shown in Figure 1.

4.2. Top-lit operation

Reed and Larson [1996] used a top-lit gasifier for cooking with a stick size of $2 \times 1 \times 0.5$ cm placed vertically in the hopper. We have also used our set-up for top-lit operation with our long-stick feed stacked horizontally. In this set-up charcoal is filled above the long-stick wood in the hopper and the charcoal is lit on the top, while the

air enters from the bottom. Air enters the bottom of the drying zone with a pyrolysis flame passing up through the fuel-wood mass. The arrangement is shown in Figure 2.

5. Performance of gasifiers

We have run the gasifier system for 25 runs in each mode. Among these runs, two for the bottom-lit mode and two for the top-lit mode have been selected and discussed.

5.1. Performance of bottom-lit (conventional) updraft operation

The gasifier system was run twice, each for a period of 5 hr 15 min in the bottom-lit updraft configuration. The time needed for the gas to support combustion from the initial flaring was 20 min in the first run and 15 min in the second run. The total wood consumption in the first run was 42 kg and in the second run 45 kg. The performance details in Run 1 and Run 2 are summarized in Table 1 and Table 2 respectively. Accordingly, with the calorific value of the producer gas at 4.2 MJ/m^3 and calorific value of the solid wood at 15.9 MJ/kg , the gasifier efficiency was found to be around 73 %.

We have examined bottom-lit updraft gasification for air flow and gas flow rates and the air/fuel ratio as shown in Tables 1 and 2. Figures 3 and 4 show operation in a combustion mode at start-up, a pyrolysis mode for the middle part of the run and a charcoal gasification mode at the end of the run. The heat release rate is unsteady in three phases, the drying phase, the pure pyrolysis phase and the charcoal burnout.

5.2. Performance of top-lit (inverted downdraft) updraft operation

The gasifier system was run twice, each for a period of

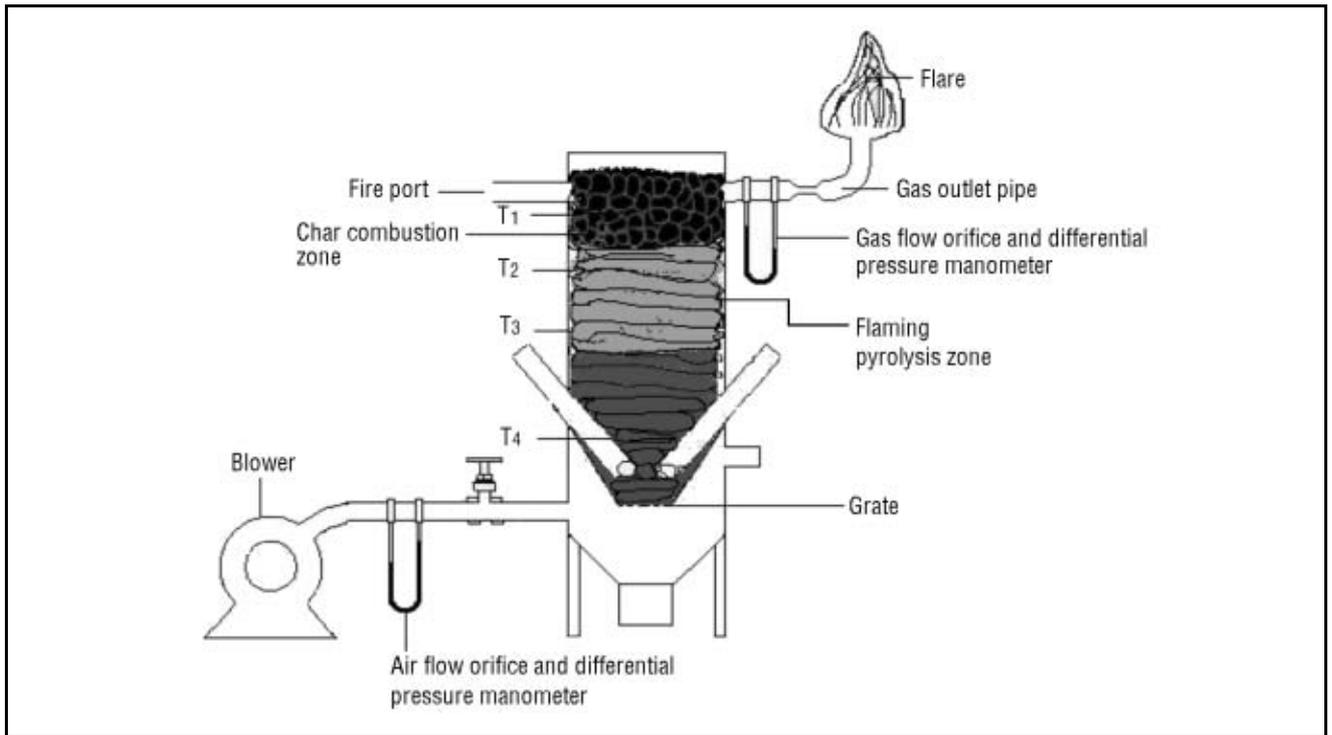


Figure 2. Schematic diagram of a top-lit updraft long-stick wood gasifier

Table 1. Run 1 performance of 5 hr and 15 min run by the bottom-lit updraft gasifier

Time (hr:min)	Flame temperature (°C)	Air flow rate (m ³ /hr)	Gas flow rate (m ³ /hr)	Fuel flow (kg/hr)	Air/fuel	Mode
0	706	23.66	27.4	4.862	6.33	Combustion
0:15	724	24.24	28.74	5.85	5.39	Combustion
0:30	748	24.81	32.42	9.893	3.26	Combustion
0:45	763	25.37	34.66	12.077	2.73	Combustion
1:00	820	26.45	44.19	23.062	1.49	Pyrolysis
1:15	833	27.49	45.85	23.868	1.5	Pyrolysis
1:30	858	28.49	47.46	24.661	1.5	Pyrolysis
1:45	869	29.45	49.02	25.441	1.5	Pyrolysis
2:00	882	29.21	51.27	28.678	1.32	Pyrolysis
2:15	896	28.24	54.12	33.644	1.09	Pyrolysis
2:30	765	24.81	41.56	21.775	1.48	Pyrolysis
2:45	642	24.24	38.75	18.863	1.67	Pyrolysis
3:00	631	23.66	35.73	15.691	1.96	Pyrolysis
3:15	622	23.06	33.56	13.65	2.2	Charcoal gasification
3:30	597	22.44	30.02	9.854	2.96	Charcoal gasification
3:45	589	21.81	28.74	9.009	3.15	Charcoal gasification
4:00	578	21.16	27.4	8.112	3.39	Charcoal gasification
4:15	552	20.49	27.4	8.983	2.97	Charcoal gasification
4:30	538	19.79	27.4	9.893	2.6	Charcoal gasification
4:45	527	19.07	27.4	10.829	2.29	Charcoal gasification
5:00	516	18.32	27.4	11.804	2.02	Charcoal gasification

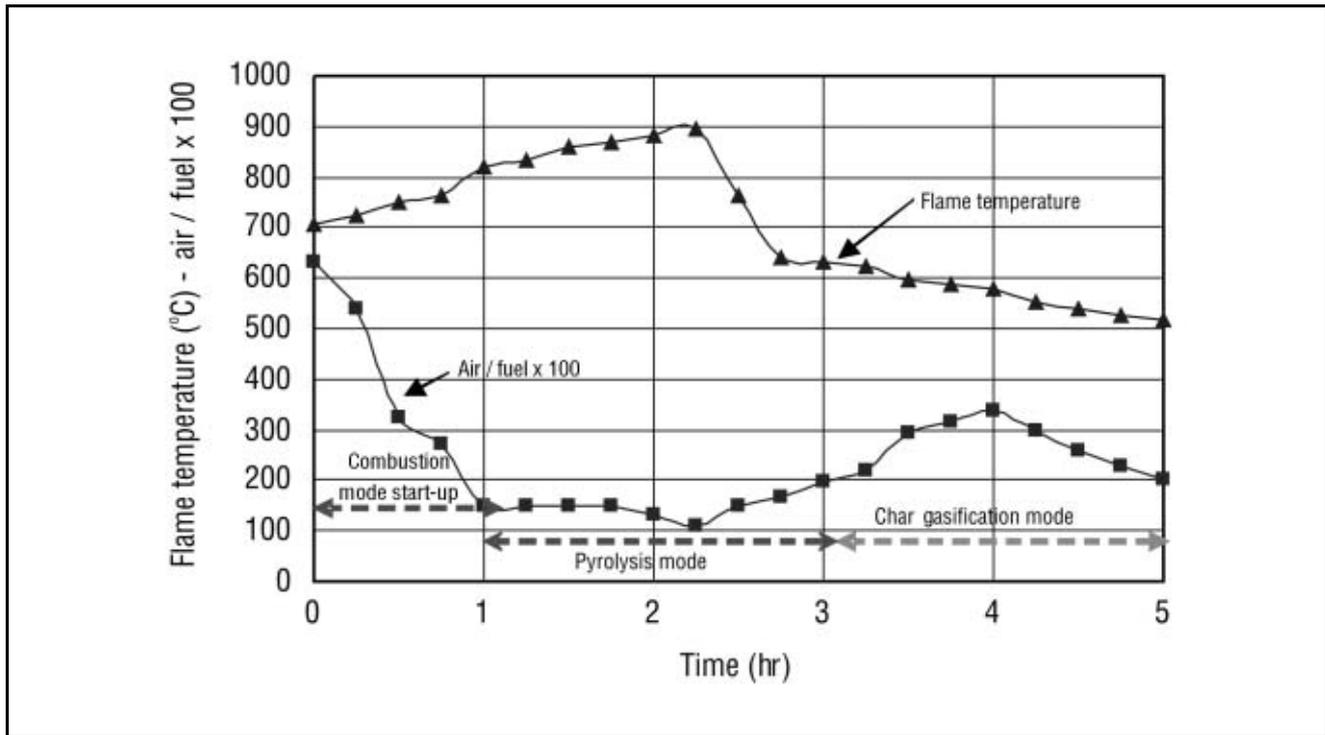


Figure 3. Bottom-lit Run 1 time vs. flame temperature - air/fuel ratio

Table 2. Run 2 performance of 5 hr 15 min run by the bottom-lit updraft gasifier

Time (hr:min)	Flame temperature (°C)	Air flow rate (m ³ /hr)	Gas flow rate (m ³ /hr)	Fuel flow (kg/hr)	Air/fuel	Mode
0	760	25.09	28.74	4.75	6.87	Combustion
0:15	734	24.24	30.02	7.51	4.19	Combustion
0:30	757	24.24	34.66	13.55	2.33	Combustion
0:45	763	24.53	45.85	27.72	1.15	Combustion
1:00	872	29.45	56.83	35.59	1.08	Pyrolysis
1:15	883	29.92	58.13	36.67	1.06	Pyrolysis
1:30	894	30.84	59.41	37.14	1.08	Pyrolysis
1:45	896	27.23	53.42	34.05	1.04	Pyrolysis
2:00	900	27.99	50.53	29.30	1.24	Pyrolysis
2:15	906	25.91	45.85	25.92	1.30	Pyrolysis
2:30	918	24.81	45.03	26.29	1.23	Pyrolysis
2:45	939	25.91	43.33	22.65	1.49	Charcoal gasification
3:00	948	24.81	42.45	22.93	1.41	Charcoal gasification
3:15	964	23.06	40.64	22.85	1.31	Charcoal gasification
3:30	987	23.36	38.75	20.01	1.52	Charcoal gasification
3:45	988	22.75	40.64	23.26	1.27	Charcoal gasification
4:00	994	21.81	38.75	22.02	1.29	Charcoal gasification
4:15	936	20.82	37.77	22.04	1.23	Charcoal gasification
4:30	933	19.79	36.76	22.06	1.17	Charcoal gasification
4:45	922	19.07	34.66	20.27	1.22	Charcoal gasification
5:00	898	17.94	33.56	20.31	1.15	Charcoal gasification

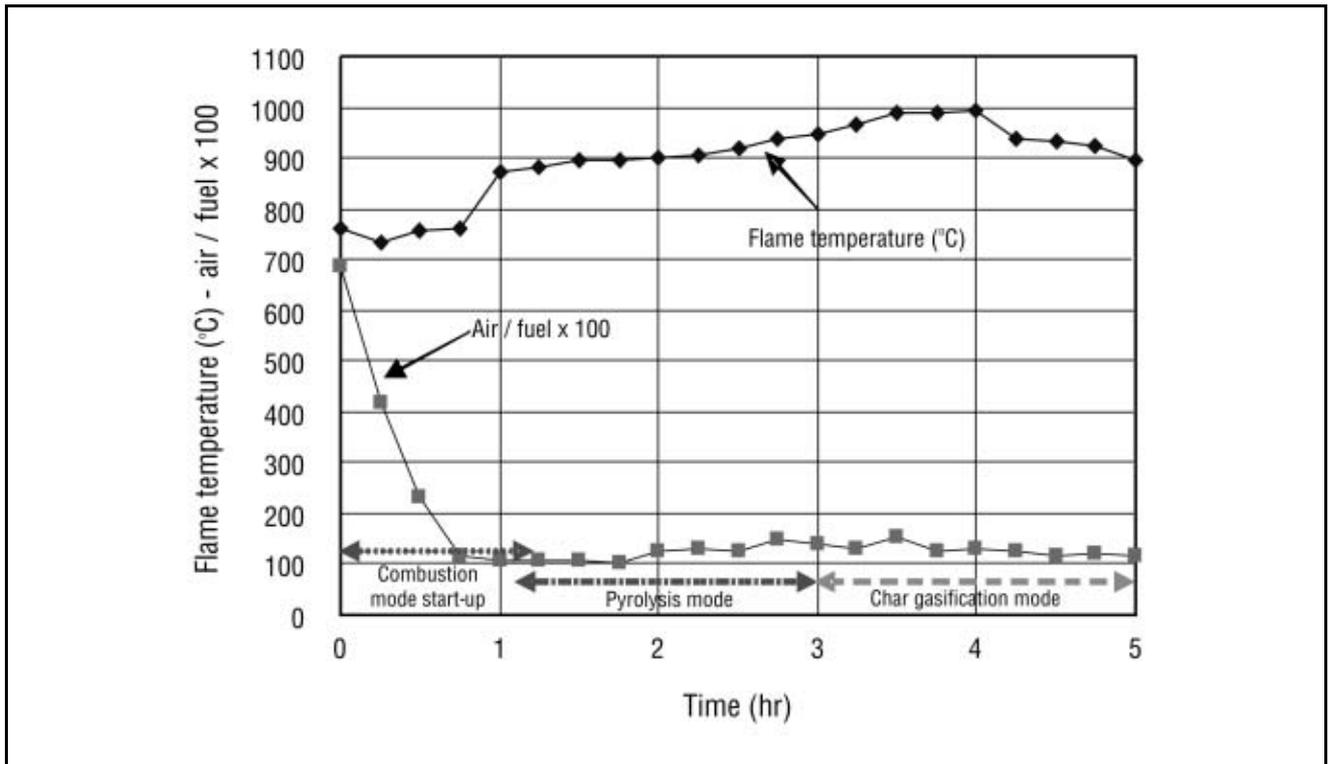


Figure 4. Bottom lit Run 2 time vs. flame temperature - air/fuel ratio

5 hr 15 min in the top-lit updraft configuration. The time needed for the gas to support combustion from the initial flaring was 15 min in the first run and 10 min in the second run. The total wood consumption in the first run was 42.5 kg and in the second run 43 kg. The performance details in Run 1 and Run 2 are summarized in Tables 3 and 4 respectively. Accordingly, with the calorific value of the producer gas at 4.2MJ/m^3 and calorific value of the solid wood at 15.9MJ/kg the gasifier efficiency was found to be around 77 %.

The top-lit mode is shown in Figures 5 and 6. Note that the flame temperature and air/fuel ratios are much more stable over a longer period of time and the average flame temperature is higher. The peak temperature at char burnout is about the same.

6. Qualitative description of top-lit updraft gasification

Observations of the behaviour of single long-stick wood particles were made during steadier heat release operation as the cylindrical feed minimises the formation of bridges and voids in the reactor leading to a well-defined, horizontal reaction zone. Figure 7 is a conceptual diagram of the observed top-lit updraft gasification processes. Top-lit updraft (inverted downdraft) gasifiers are true gasifiers in that they burn the volatiles to make charcoal, and then pass the gas and volatiles through the charcoal to convert tar and char to more gas. With dry fuels they can make more than 20 % charcoal to be used later and this charcoal has as much value as the heat from the volatile combustion in many parts of the world.

The fuel-wood is lit on the top and forms a layer of

charcoal. The flaming pyrolysis zone is below that and the unprocessed wood is at the bottom of the pile. The primary air for pyrolytic gasification enters at the bottom and moves up, forming gas in the flaming pyrolysis zone as shown in Figure 7. This can be operated on forced draft or natural draft mode. We have examined the quantity and the nature of the ash collected after the different performance trials. As expected, the quantity of ash collected in the top-lit mode is smaller compared with that in the bottom-lit mode. The quality of the gas is also better due to the cracking of tar in the top-lit mode.

7. Mathematical model of bottom-lit updraft gasifier physical process

10 kg of charcoal is placed on a grate and ignited at two fire ports. It appears that the blower is run in suction mode to draw air in through the fire ports during the charcoal ignition. 60 kg of long-stick wood is placed on top of the charcoal. The fire ports are closed and the flame supplied through the two fire ports stops. The fan is run in blower mode and the air enters from below the bed. This air flow is measured by pressure drop across a restriction. Gases produced by the wood and charcoal exit through a gas port. This gas is combusted and the gas flow rate (via pressure difference) and the producer gas flame temperature are recorded. Drying, pyrolysis, and combustion of the packed bed continue until the flame at the gas port goes out.

In order to understand the process of gasification it was found desirable to develop a mathematical model. The earlier study of Buekens and Schoeters [1983] was based on the mass and energy balances, as well as equilibrium data

Table 3. Run 3 performance of 5 hr 15 min run by the top-lit updraft gasifier

Time (hr:min)	Flame temperature (°C)	Air flow rate (m ³ /hr)	Gas flow rate (m ³ /hr)	Fuel flow (kg/hr)	Air/fuel	Mode
0	630	23.66	27.4	4.862	6.33	Combustion
0:15	724	24.24	28.74	5.85	5.39	Combustion
0:30	735	24.81	32.42	9.893	3.26	Combustion
0:45	746	25.37	34.66	12.077	2.73	Combustion
1:00	748	26.45	36.76	13.403	2.57	Flaming pyrolysis
1:15	758	27.49	45.85	23.868	1.50	Flaming pyrolysis
1:30	765	28.49	47.46	24.661	1.50	Flaming pyrolysis
1:45	776	29.21	49.02	25.753	1.47	Flaming pyrolysis
2:00	780	30.2	49.8	25.48	1.54	Flaming pyrolysis
2:15	795	30.84	51.3	26.598	1.51	Flaming pyrolysis
2:30	805	31.74	53.4	28.158	1.47	Flaming pyrolysis
2:45	808	33	55.5	29.25	1.47	Flaming pyrolysis
3:00	802	34.5	58.1	30.68	1.46	Flaming pyrolysis
3:15	810	33.5	54.8	27.69	1.57	Flaming pyrolysis
3:30	830	33	55.5	29.25	1.47	Flaming pyrolysis
3:45	846	30.2	49.8	25.48	1.54	Flaming pyrolysis
4:00	864	28.5	47.5	24.7	1.50	Flaming pyrolysis
4:15	886	25.1	42.5	22.62	1.44	Charcoal gasification
4:30	762	24.2	38.8	18.98	1.66	Charcoal gasification
4:45	650	24	36.8	16.64	1.88	Charcoal gasification
5:00	620	23.77	27.4	4.719	6.55	Charcoal gasification

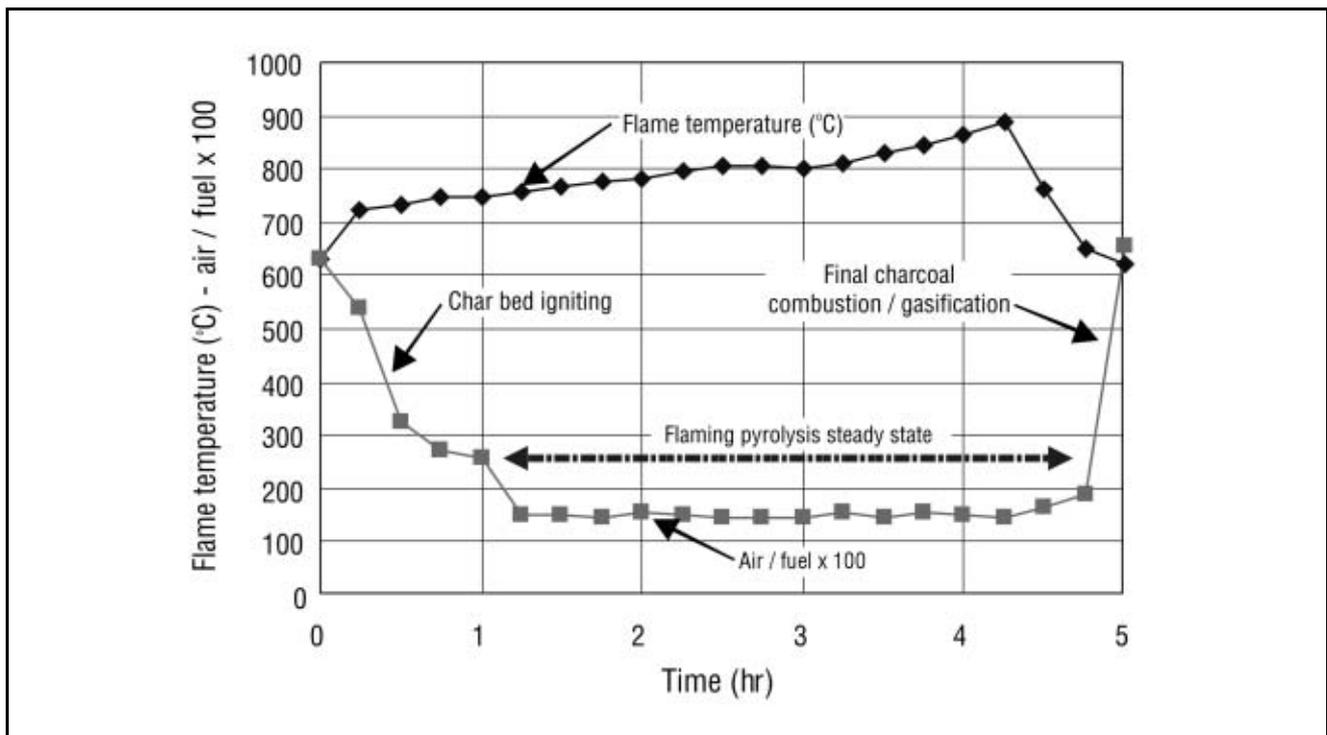


Figure 5. Top-lit Run 3 time vs. flame temperature - air/fuel ratio

Table 4. Run 4 performance of 5 hr 15 min run by the top-lit updraft gasifier

Time (hr:min)	Flame temperature (°C)	Air flow rate (m ³ /hr)	Gas flow rate (m ³ /hr)	Fuel flow (kg/hr)	Air/fuel	Mode
0	600	25.09	28.74	4.75	6.87	Combustion
0:15	734	24.24	30.02	7.51	4.19	Combustion
0:30	757	24.24	34.66	13.55	2.33	Combustion
0:45	784	24.53	45.85	27.72	1.15	Combustion
1:00	798	29.45	56.83	35.59	1.08	Flaming pyrolysis
1:15	805	29.92	58.13	36.67	1.06	Flaming pyrolysis
1:30	812	30.84	59.41	37.14	1.08	Flaming pyrolysis
1:45	820	27.23	53.42	34.05	1.04	Flaming pyrolysis
2:00	835	27.99	50.53	29.30	1.24	Flaming pyrolysis
2:15	840	25.91	45.85	25.92	1.30	Flaming pyrolysis
2:30	855	24.81	45.03	26.29	1.23	Flaming pyrolysis
2:45	863	25.91	43.33	22.65	1.49	Flaming pyrolysis
3:00	874	24.81	42.45	22.93	1.41	Flaming pyrolysis
3:15	878	23.06	40.64	22.85	1.31	Flaming pyrolysis
3:30	895	23.36	38.75	20.01	1.52	Flaming pyrolysis
3:45	910	22.75	40.64	23.26	1.27	Flaming pyrolysis
4:00	925	21.81	38.75	22.02	1.29	Flaming pyrolysis
4:15	933	20.82	37.77	22.04	1.23	Charcoal gasification
4:30	935	19.79	36.76	22.06	1.17	Charcoal gasification
4:45	956	19.07	34.66	20.27	1.22	Charcoal gasification
5:00	998	18.32	33.56	20.31	1.15	Charcoal gasification

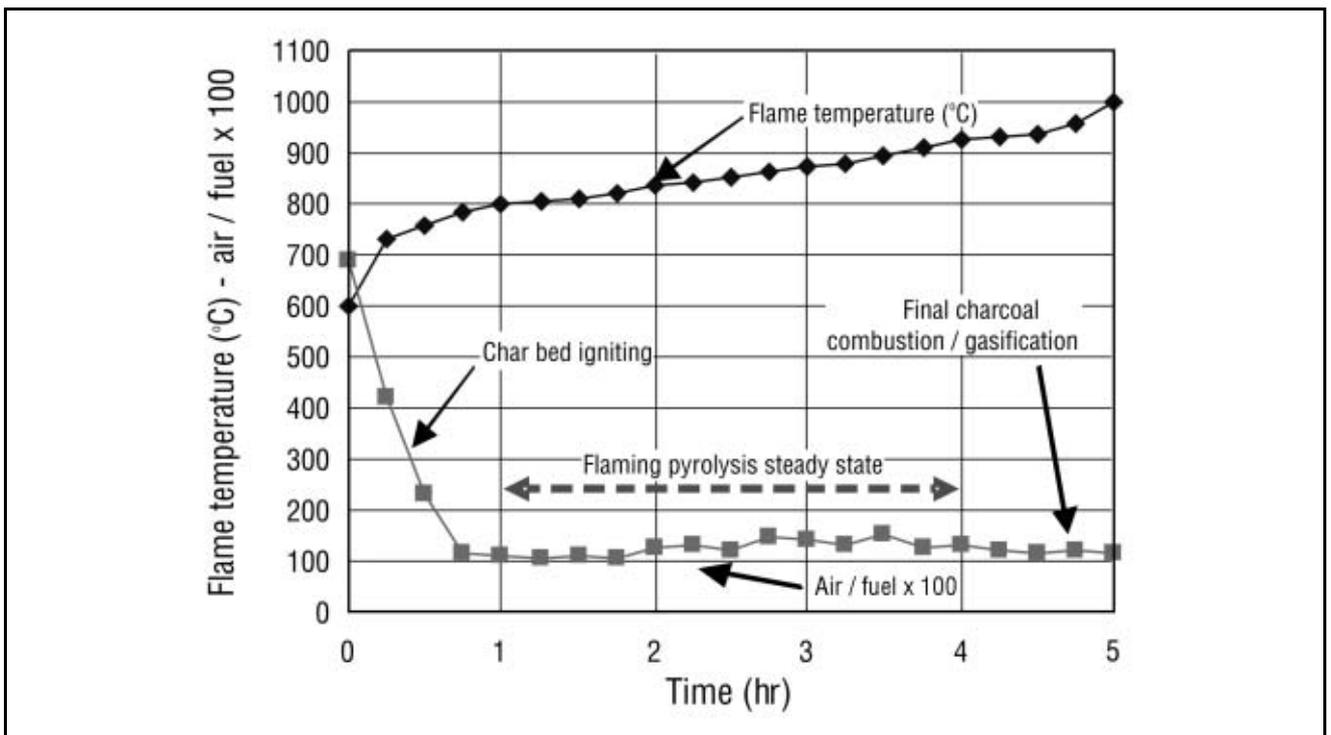


Figure 6. Top-lit Run 4 time vs. flame temperature - air/fuel ratio

and rate laws, following [Reed and Levie, 1984]. We employed here a kinetic free model, in which the gasifier is subdivided into four different zones. The gas outlet in the gasifier is calculated from equilibrium data whereas the reaction temperature is calculated in each zone by a separate heat and mass balance. The model is confined to the bottom-lit set-up and in practice can be adopted for the top-lit case as well.

Assumptions

1. The reactor is closed.
2. The process is adiabatic because there is no external heat transfer and temperature remains constant within the closed reactor.
3. It is a kinetic free model, in which the gasifier is subdivided into four different zones. The gas output in the gasifier is calculated from equilibrium data whereas the reaction temperature is calculated in each zone by a separate heat and mass balance. Heat and mass transfer are limited to being kinetic free.
4. The convective heat transfer during flaming pyrolysis passes up to the pyrolysis zone.
5. We have assumed the time taken for each zone is:

drying process	: 2 min
pyrolysis process	: 4 min
reduction process	: 2 min
combustion process	: 2 min

We have assumed the bottom layer is composed entirely of charcoal (essentially just carbon atoms). Air enters at a specified velocity, and combustion of the charcoal particles occurs according to the $2C + O_2 \rightarrow 2CO$ reaction rate. As the char bed heats up, forced flow (by a fan) causes gases to heat up as they travel through the charcoal bed (via convective heat transfer). When these gases travel through the wood portion of the bed, convective heat transfer occurs from the gases to the solid wood particles, helping to heat and gasify the wood region, as shown in Figure 8. Radiation also causes heat transfer in both the char and wood regions. When the combustion zone produces the heat energy, it is transferred from bottom to top. The conventional updraft gasifiers with the reaction zone at the bottom are really pyrolyser tar producers, burning the charcoal on the grate to generate heat to pyrolyse the incoming fuel and making more condensable vapours (up to 20 %) than gas.

We have described the system as a one-dimensional series of particles, 10 charcoal particles stacked on top of one another with 10 wood particles stacked on top of the char particles. In the model, radiation travels from a charcoal particle to the particle directly above it and to the particle directly below it. For the top charcoal particle radiation travels to the charcoal particle below it and radiation travels to the bottom wood particle. For the top wood particle and the bottom charcoal particle, radiation occurs to the radiative background temperature, which is currently 30° C but can be changed. In a real bed of particles, radiation can travel further than from adjacent particle to adjacent particle, depending on the relative view factor between particles. The present model will underes-

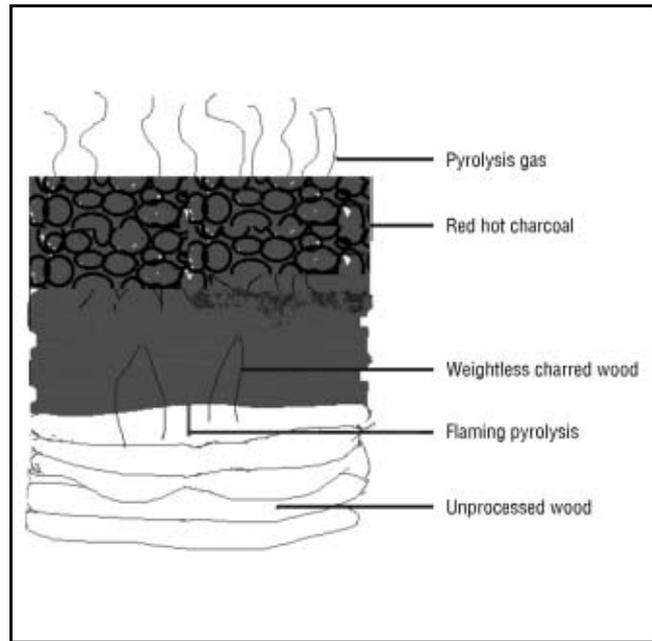


Figure 7. Reactions within the top-lit updraft long-stick wood gasification

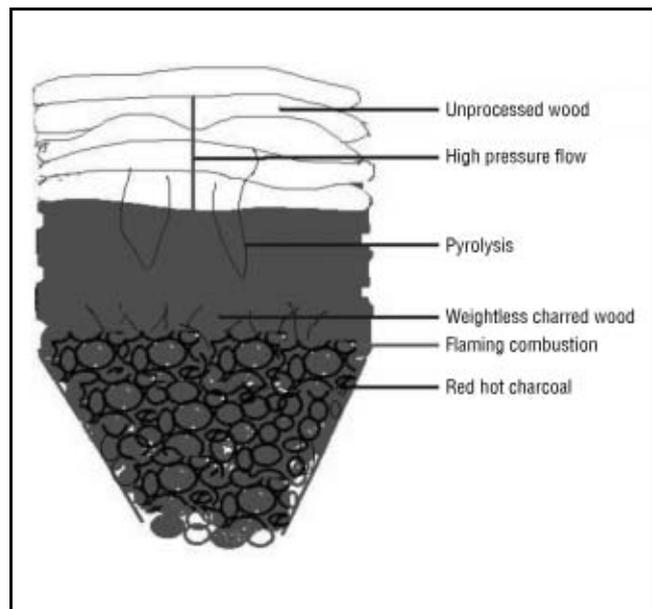


Figure 8. Reactions within the bottom-lit updraft long-stick wood gasification

imate radiation because of the assumption of the model. The other issue with radiation is that the bottom charcoal particles burn first (more O_2). The underestimate of the radiation means that there should be some radiation to the 1 cm particle, and some radiation that travels beyond the 1 cm particle to the background. This is particularly important to account for the fact that the char reaction rate used currently causes very high temperatures in the charcoal. (Heat generation becomes greater than heat losses for very small particles.)

The exact nature of radiation is complex, because the hot combustion gases are participating media, and radiation can occur from particle to particle. Hot combustion gases surrounding a charcoal particle will radiate to the particle surface. The charcoal particle will also radiate to

Table 5. Model equations

Drying zone	
Heat balance	
$\frac{\partial}{\partial t} \sigma A T^4 = \frac{\partial}{\partial t} m C_p (T - T_i) + \frac{\partial}{\partial t} h_c (T - T_i) + h_c \frac{dM}{dt}$	(1)
Mass balance	
$\frac{\partial \rho_{\text{virgin wood}}}{\partial t} = \frac{\partial}{\partial t} (\rho_m + \rho_{\text{wood}})$	(2)
Pyrolysis zone	
Heat balance	
$\frac{\partial}{\partial t} h_c (T-T_i) = \frac{\partial}{\partial t} (m_{\text{pyr}} + m_g) h_{\text{pyrg}} + \frac{\partial}{\partial t} m_{\text{pyr}} C_{\text{ppyr}} (T-T_i)$	(3)
Mass balance	
$\frac{\partial \rho_{\text{pyr}}}{\partial t} = \frac{\partial}{\partial t} \rho_{\text{pyr}} - \rho_{\text{wood}}$	(4)
Reduction zone	
Heat balance	
$\frac{\partial}{\partial t} [h_c (T_1-T_2)] = \frac{\partial}{\partial t} m_g c_g (T_1-T_2)$	(5)
Mass balance	
$\frac{\partial \rho_{\text{charcoal}}}{\partial t} = \frac{\partial}{\partial t} (\rho_{\text{gas}})$	(6)
Gas = producer gas = CO + H ₂	
Combustion zone	
Heat balance	
$\frac{\partial}{\partial t} [\sigma A (T^4 - T_i^4)] = \frac{\partial}{\partial t} m_g c_g (T-T_i) + \frac{\partial}{\partial t} M_c C_c (T-T_i)$	(7)
Mass balance	
$\frac{\partial \rho_{\text{charcoal}}}{\partial t} = \frac{\partial}{\partial t} (\rho_{\text{gas}})$	(8)
Gas = CO + H ₂	

Note

See "Explanations of symbols" after the main text of this paper.

adjacent solid particles. A charcoal particle is at 727° C (1000 K) and has neighbours at 627° C (900 K) and 827° C (1100 K) and external gases around it at 1027° C (1300 K).

With a 90 % radiation parameter, and each particle having a surface area of A,
 $Q_{\text{net}} = 0.90 \times \sigma \times A \times (1300^4 - 1000^4)$ (radiation from gases) + $0.05 \times \sigma \times A \times (1100^4 - 1000^4)$ (radiation to adjacent particle) + $0.05 \times \sigma \times A \times (900^4 - 1100^4)$ (radiation to adjacent particle), where σ is the Stefan-Boltzmann constant.

The radiation term for the gas would be

$Q_{\text{net}} = 0.90 \times \sigma \times A \times (1100^4 - 1300^4)$ (radiation from particle)

Convective heat transfer will also occur between the gases and the solid as in the current version of the model. Conductive heat transfer occurs in the gas region, and within the solid wood particles. Charcoal particles are assumed to be at a constant temperature, so no conduction is assumed within the particle.

The fuel is combusted according to the rate of air flow and the ignition temperature of the bed. As the charcoal burns, a temperature and oxygen profile develops within the lower portion of the bed. Through convective and radiative heat transfer, regions of combustion, reduction, drying, and pyrolysis form according to conservation of energy ($Q_{\text{in}} - Q_{\text{out}} = \text{stored energy}$) and conservation of mass within different regions of the bed.

In this connection, Equation 1 in Table 5 below explains that heat energy radiated by air inside the gasifier due to burning of long-stick woody biomass is equal to heat gained by wood from inside air and energy used in moisture evaporation. The model proposed in [Saastamoinen, 1992] confines attention only to the drying and pyrolysis zones. It examines the moisture content of wood, particle size, gas flow velocity and wood mass flow rates in the context of the drying and pyrolysis sections with the convective heat transfer during flaming pyrolysis passing up or down to the pyrolysis zone. In our present work, we have examined the heat transfer in all the four zones from combustion zone to drying zone. The model equation is shown in Table 5.

For the optimal design of different gasifiers using large fuel particles, it is necessary to know the effect of the moisture release rate, since the fuel is seldom completely dried before combustion. Saastamoinen and Richard [1988] found that for a large solid fuel particle, drying and pyrolysis are locally successive processes but when considering the particle as a whole the processes are actually overlapping. Local thermal equilibrium between gas and solid is assumed in the one-dimensional Equations 3 and 4 above. The left-hand side of these equations describes the heat transferred by the convective process and the right-hand side describes the heat gained by release of pyrolysis vapours and gases. For large wood particles, the pyrolysis becomes controlled by the heat transfer in the particle. Mukunda et al. [1984] and Saastamoinen et al. [1993] studied the energy feedback from the combusting volatiles around the particle to the particle surface. For combusting particles, the flame around the particle increases the heat transfer and the drying and the pyrolysis rate. In the reduction zone, Equations 5 and 6 describe the heat and mass transferred by the convection due to the production of wood gas and the heat gained by the producer gas. Bridgwater [1995] reports that the energy efficiency and stable operation of wood gasification technologies are influenced by the reactivity of the chars produced in the pyrolysis stage mainly because the char conversion is often the slowest. In the combustion zone, Equations 7 and 8 describe the radiation heat transferred

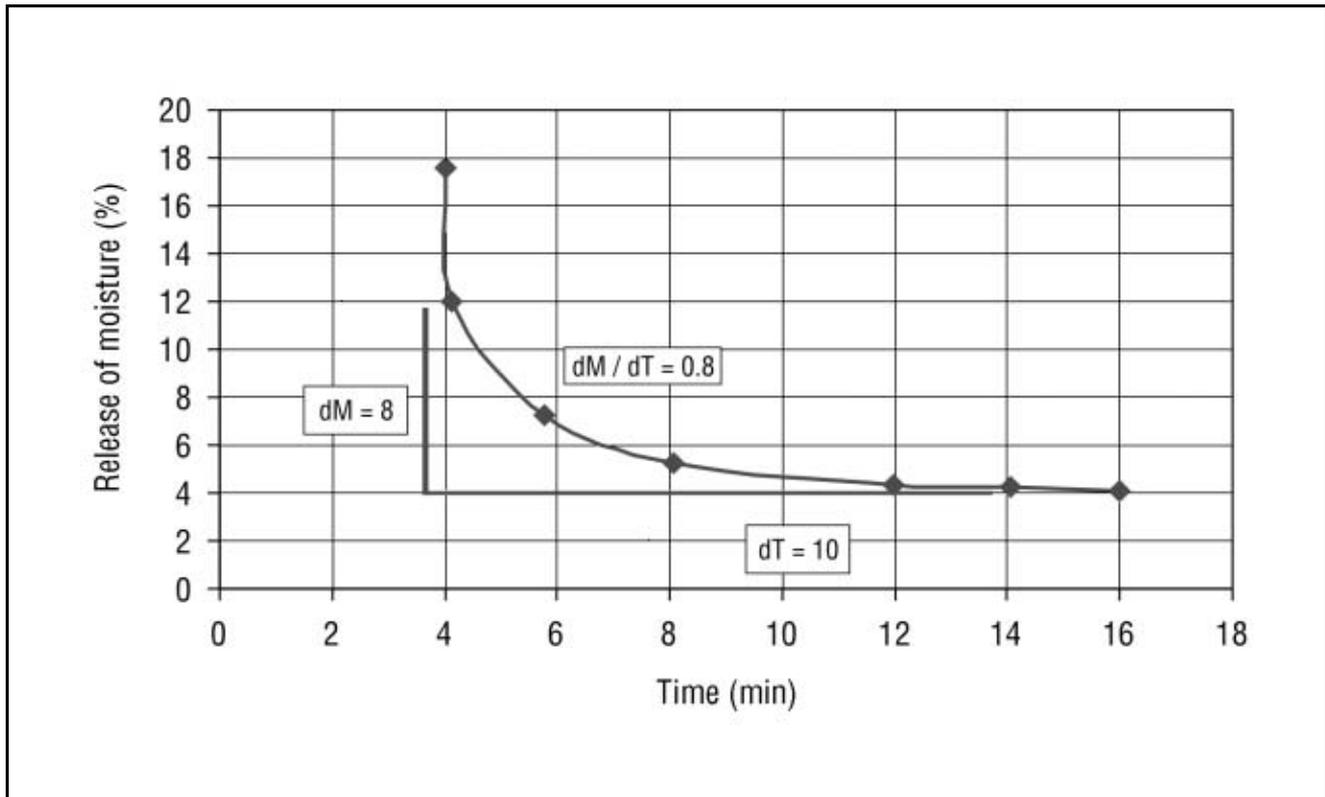


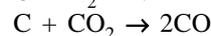
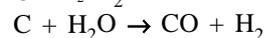
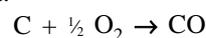
Figure 9. Release of moisture vs. time

from a charcoal particle to the particle directly above it and to the particle directly below it. For the top charcoal particle radiation travels to the charcoal particle below it and radiation travels to the bottom wood particle. As the charcoal burns, temperature, oxygen profile and gas develop within the lower portion of the bed.

When wood is heated slowly at low temperature to produce charcoal, the char is relatively solid without substantial splitting and cracking. This splitting and cracking allows convective heat and mass transfer and radiative heat transfer from the free stream deep within the char structure. Visually observing the patterns on the char surface is one popular way of using wood to interpret a fire scene. Bryden and Ragland [1997] have studied single wood logs combusted at furnace level heat fluxes. On the basis of Bryden's work Saravanakumar and Haridasan [2002] attempted to thermally crack wood logs by initially flaming them in a chamber. The cracking starts at about 253-276° C and the splitting takes place at about 300° C. At 237° C, a small crack takes place in the wood. From a visual examination, cracks, extending from the surface of the particle to the char front deep inside these cracks, extend slightly deeper than the char front into the unreacted wood. The time taken for cracking is about 120 sec. The ratio of volume loss of wood per sec to volume loss of the wood used is found to be 0.0015, indicating the long-range feasibility of adopting this method. It is likely that thermal cracking relieves high internal gas pressures developed during the drying of the wood. In addition, shrinkage caused by the structural change from wood to char creates internal stresses, which are relieved by ther-

mal cracking. The char layer also shrinks and pressure gradients are set up within the material. Small cracks appear on the surface, and these cracks allow volatiles to escape more easily. After the volatiles have been exhausted, flaming ceases and a solid char residue remains. The char continues to burn in a smouldering mode. Before that, char oxidation is usually minimal since the flame prevents diffusion of oxygen to the surface. Therefore, the heat release rate and related quantities measured during the flaming phase are predominantly those of the volatiles. However, for a period both surface oxidation and discrete surface flameless at the wood cracks can coexist. A limited number of studies have dealt with the relation between the pyrolytic conditions and either char reactivity or char structure during biomass gasification.

Char combustion is a complex process of intrinsic gas solid interactions at the atomic level. Gas molecules separate and are adsorbed into active sites of the char surface, attaching themselves to char. These gases are then desorbed with the attached char components. The global reaction rates depend very much on the type of char or carbon material. The following three char equations are of much interest.



The values of dM/dT to be inserted in the governing equation were obtained by examining the moisture release of the feed in the drying zone at different time intervals and plotting that as a function of time as indicated in Figure 9.

Table 6. Numerical values in the different zones in the gasifier

Different zones in the gasifier	Equation no.	Numerical values (J) of the l.h.s. and r.h.s. of the equations before differentiation with respect to t					
		T ₀		T ₀ +1 min		T ₀ +2 min	
		l.h.s.	r.h.s.	l.h.s.	r.h.s.	l.h.s.	r.h.s.
Drying	1	878.69	878.74	895.79	893.92	910.2	909.2
Pyrolysis	3	64.91	64.91	71.40	70.67	77.89	77.87
Reduction	5	84.38	82.50	110.34	110.00	168.76	165.22
Combustion	7	1847.6	1848	1954	1925	2057.3	2040.5

The values of C_c and C_g (1.1 J/kg K, 1.1 J/kg K) are taken from [Di Blasi and Russo, 1992]. The value of C_{ppyr} (2.4 J/kg K) is similarly taken from [Bryden et al., 2002].

8. Results and discussion

We have examined bottom-lit and top-lit updraft gasification and calculated the air/fuel ratio as shown in Figures 3-6. The bottom-lit case Figures 3 and 4 show operation in a combustion mode at start-up, a pyrolysis mode for the middle part of the run and a charcoal gasification mode at the end of the run. The top-lit mode is shown in Figures 5 and 6. Note that the flame temperature and air/fuel ratios are much more stable over a longer period of time and the average flame temperature is higher. The peak temperature at char burnout is about the same.

8.1. Validation of the heat balance equation of the measured data

The validity of Equations 1, 3, 5 and 7 is tested by estimating the left-hand side (l.h.s.) and right-hand side (r.h.s.) contributions at $T = T_0$, $T = T_0 + 1$ min and $T = T_0 + 2$ min. Values of the functions on l.h.s. and r.h.s. agree as can be seen from Table 6 at different times and hence the time derivatives naturally agree well. In the experience of long-stick wood gasification, such a model is very critical when compared to the cases of wood particles, pellets, and char, etc. The temperature at a location rises first in the combustion zone and then rises smoothly through the pyrolysis and drying zones. When the wood is completely charred, the temperature increases. In the pyrolysis section steady state, temperature ranges between that of the hot combustion surfaces and that of the cold unreacted core. The temperature was measured as a function of time at 15 min intervals at the layers from the bottom to the top surface of the gasifier. The temperature ranges from 922° C in the combustion zone to 128° C in the drying zone. In all the zones, the heat balance equations show a good fit between the theoretical and experimental values.

8.2. Results on velocity of fuel flow in the gasifier

Saastamoinen [1994] has studied the modelling of wood gasification in an updraft mode. In this, the gasifier was operated by lowering the air rate below a critical value, increasing the bed height without limit. We have operated the updraft mode on the basis of high-energy release rate

per unit area due to high inlet air velocity and activated reaction in the combustion zone. If long-stick wood is added on top of the burning charcoal, it will be pyrolysed by the heat, giving a mixture of gases and volatile condensable compounds. As they are generated, the charcoal is replenished, so that a steady state can be reached by adjusting the rate of wood feed. We have estimated the velocity of motion of fuel in the gasifier as a function of the amount of wood being gasified and it is found to be 0.74 cm/sec (after [Reed et al., 1988]). In our experience, the updraft gasifier is found to be suitable for long-stick woody biomass materials with high inlet air velocity.

8.3. Effect of heat release rate on temperatures within the gas

Figure 10 shows for the bottom-lit case, that the heat release rate is unsteady in three phases, the drying phase, the pure pyrolysis phase and the charcoal burnout. Initially during the first 2 hr of operation a temperature of around 700-896° C is obtained. After 3 hr, the temperature will be reduced.

Figure 11 shows that for the top-lit case the heat release rate is steady in three phases, the drying phase, the pure pyrolysis phase and the charcoal burnout.

8.4. Effects of temperature in different zones of the gasifier

The long-stick wood gasifier was tested for different air-flow rates: 25, 35, 38, 45, 50 and 53 m³/hr. The temperature profile of different zones as a function of air-flow rate is shown in Figure 12. The graph indicates the high energy release rate per unit area due to high inlet air velocity and activated reaction in the combustion zone. When the air is directly getting into the combustion zone, a high temperature is obtained.

8.5. Effects of air velocity and gas flow rates on the gasifier

Figure 13 shows the gas production rate increasing with increase of inlet air velocity linearly and steadier gas production up to an air velocity of 1.96 m/sec. For inlet air velocity ranging from 2.25 m/sec to 2.64 m/sec, the gas production increases faster. It is obvious that the gas production rate would show a similar behaviour with the change in air-flow rate. We have estimated the air velocity of motion of inlet air in the gasifier as follows.

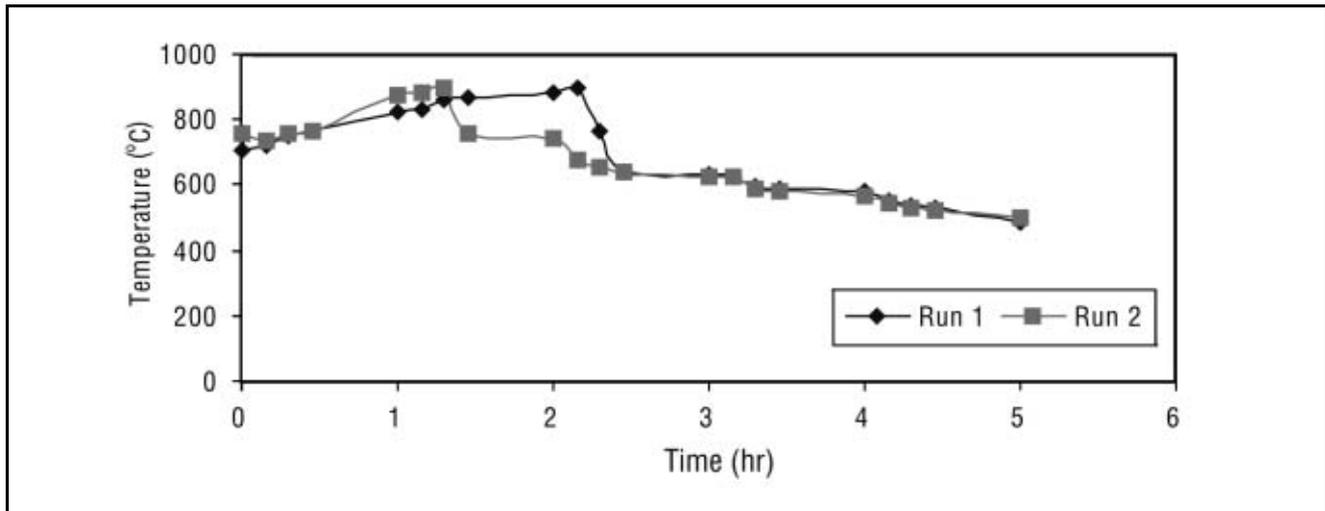


Figure 10. Time vs. gas temperature (bottom-lit updraft runs)

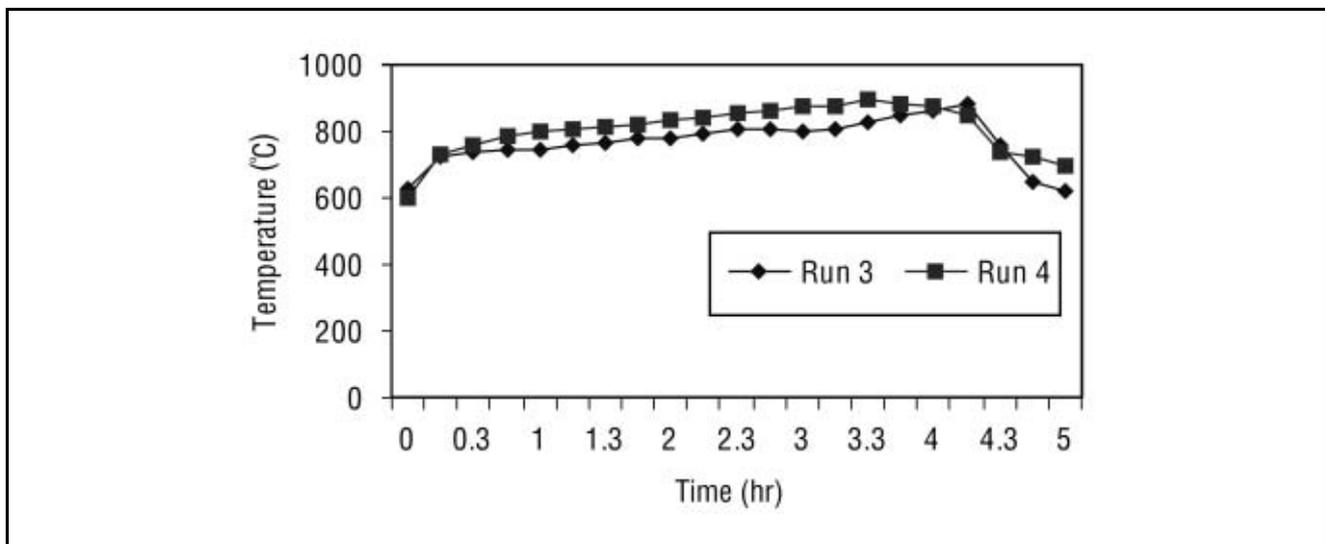


Figure 11. Time vs. gas temperature (top-lit updraft runs)

$$\begin{aligned} \text{Air velocity} &= \text{Air-flow rate/area of the flow pipe} \\ &= 0.0051 \text{ m}^3/\text{sec}/0.0031 \text{ m}^2 = 1.64 \text{ m/sec} \end{aligned}$$

9. Conclusions

The experience of gasifier users with regard to the effort and energy needed for wood chip preparation in a typical gasifier has led us to the development of a gasifier suitable to work with long-stick woody biomass as the feed material. In the spirit of using an energy plantation for such a gasifier system, it is preferable to obtain such sticks from the branches of trees, which can be replenished at the plantation site in a shorter time-span as compared to big trees being cut.

For the modelling, the gasifier was divided into a drying zone, a pyrolysis zone, a combustion zone and a reduction zone. In all the zones, the heat balance equations show a fairly good fit between the theoretical and experimental values. With this concept, a 25m³/hr capacity gasifier was designed and constructed. An experimental investigation of bottom-lit updraft and top-lit updraft gasifiers was carried out using long-stick wood under various

air-flow rate operating conditions. For the bottom-lit updraft operation, the heat release rate was unsteady in three phases: the drying phase, the pure pyrolysis phase and the charcoal burnout. In the top-lit updraft condition, the heat release rate was steady in three phases: the drying phase, the flaming pyrolysis phase and the charcoal burnout. The quantity of ash collected in the top-lit mode is smaller compared with that in the bottom-lit mode. The quality of the gas was also better in the top-lit mode due to the cracking of tar.

This gasifier attained a high energy release rate per unit area due to high inlet air velocity and activated reaction in the combustion zone. The gas production rate increased with increase of inlet air velocity linearly and showed steadier gas production up to an air velocity of 1.96 m/sec. The rate of feed was between 9 and 10 kg/hr and continuous batch-mode operation for 6 hr was maintained in a couple of runs to study the performance. The velocity of motion of fuel in the gasifier is a function of the amount of wood being gasified and is found to be 0.74 cm/sec. The temperature ranged from 922° C in the combustion zone to 128° C in

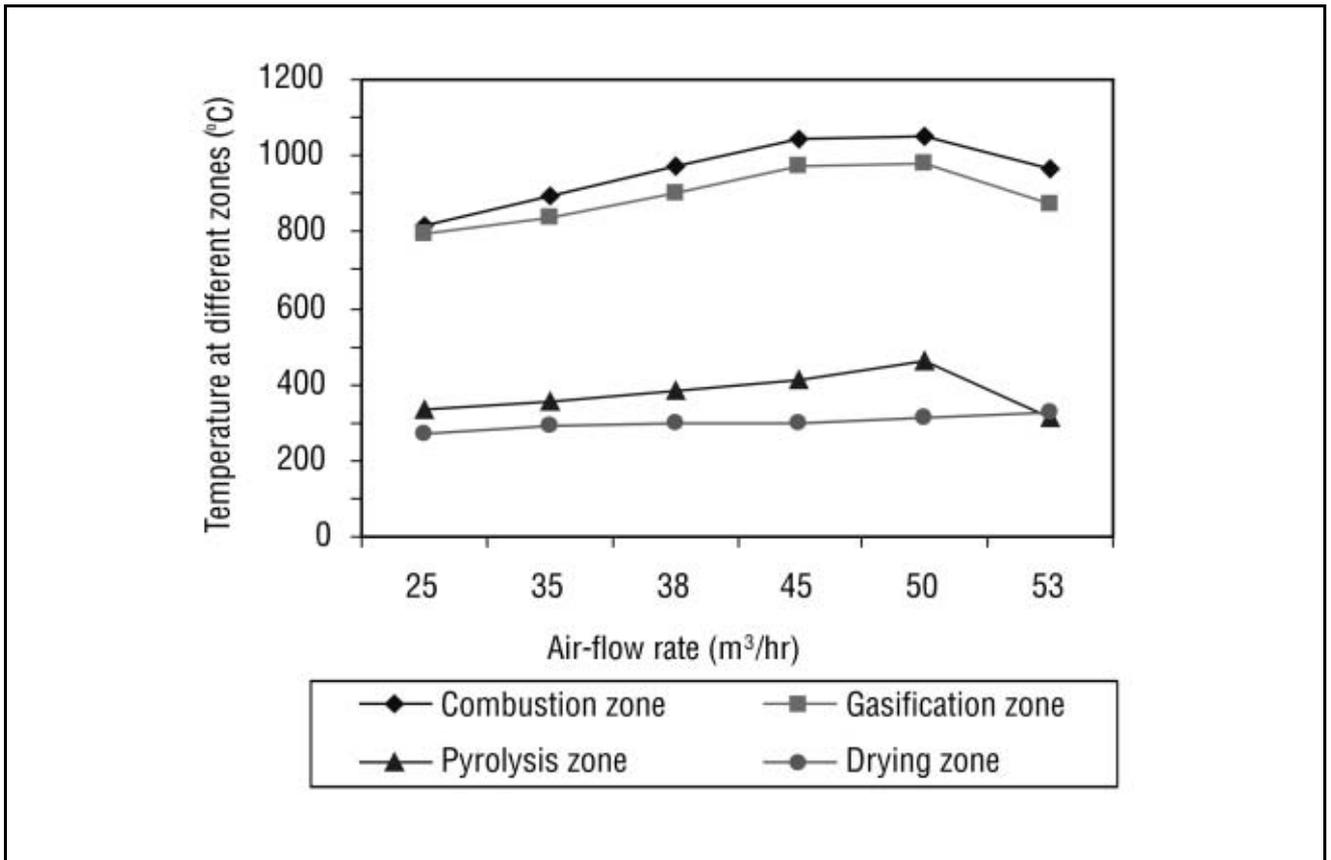


Figure 12. Temperature found at different zones in the gasifier

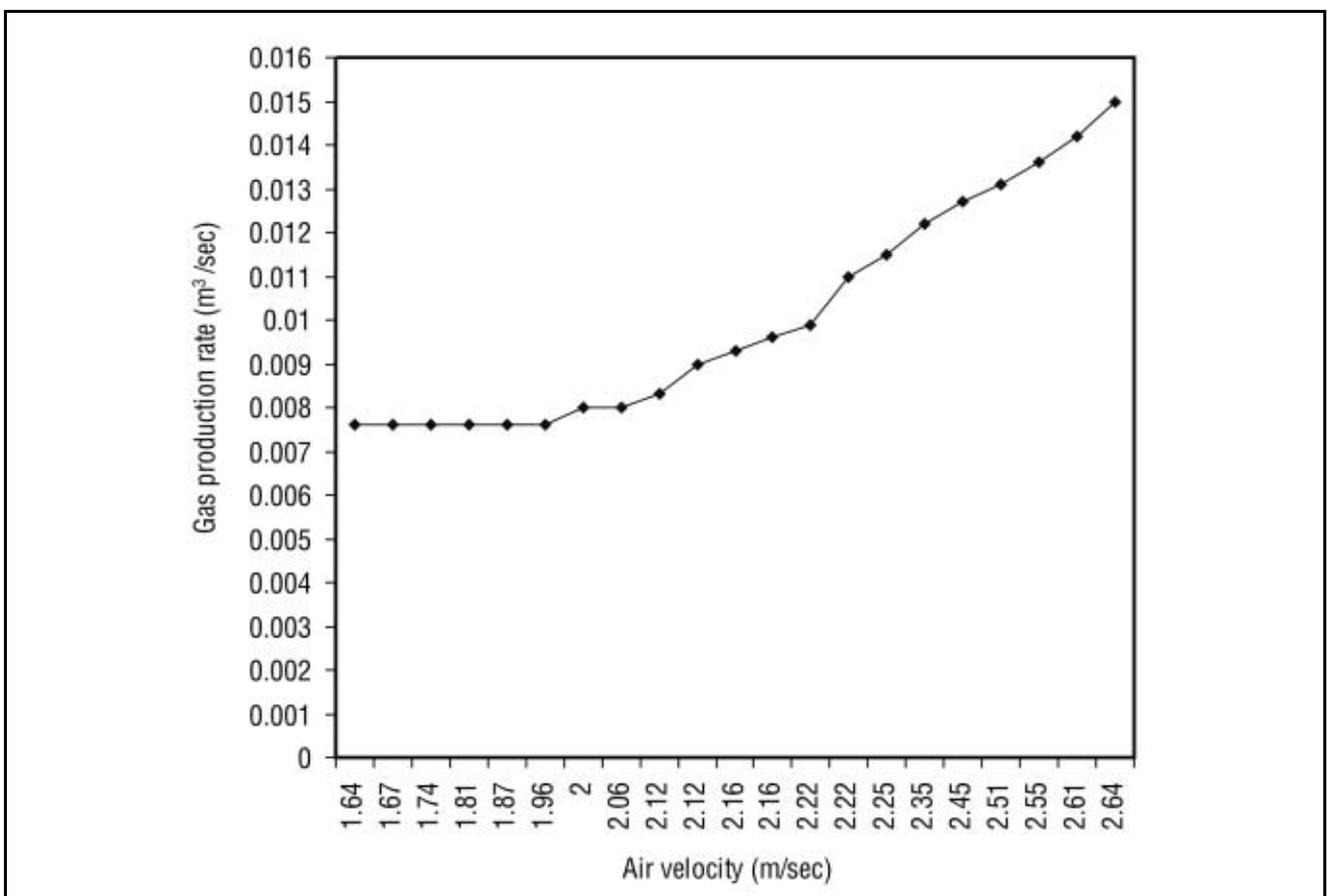


Figure 13. Air velocity vs. gas production rate

the drying zone. The gas and air flows can be converted into the air/fuel ratio (A/F), the most important aspect of gasifier operation. A/F values of 6.33, 1.49 and 2.0 showed operation in a combustion mode at start-up, a pyrolysis mode for the middle part of the run and a charcoal gasification mode at the end of the run respectively. The efficiency of the bottom-lit and top-lit updraft long-stick wood gasifier was found to be 73 % and 75 % respectively. ■

Explanations of symbols

Q_{net}	- Stored Energy, J (Qin-Qout=Stored Energy)
σ	- Stefan-Boltzmann constant, $W\ m^{-2}\ K^{-4}$
A	- Area of the particular zone, m^2
h_c	- Convective heat transfer coefficient, $W\ K^{-1}$
T	- Final temperature of the particular zone, K
T_i	- Initial temperature of the particular zone, K
h_g	- Enthalpy of moisture evaporation, $J\ kg^{-1}$
m_{air}	- Mass of air, kg
C_{pa}	- Specific heat of air, $kJ\ kg^{-1}\ K^{-1}$
C_{ppyr}	- Specific heat of pyrolysis products, $kJ\ kg^{-1}\ K^{-1}$
C_c	- Specific heat of char, $kJ\ kg^{-1}\ K^{-1}$
C_g	- Specific heat of gas, $kJ\ kg^{-1}\ K^{-1}$
$h_{pyr\ g}$	- Heat of vaporization of pyrolysis and gaseous products, $J\ kg^{-1}$
ρ_m	- Moisture density, $kg\ m^{-3}$
ρ_{wood}	- Density of long stick wood, $kg\ m^{-3}$
ρ_{pyr}	- Density of pyrolysis products, $kg\ m^{-3}$
ρ_{charcoal}	- Density of charcoal, $kg\ m^{-3}$
ρ_{gas}	- Density of gas, $kg\ m^{-3}$
m_{pyr}	- Mass of pyrolysis, kg
m_g	- Mass of gas, kg
m_c	- Mass of char, kg

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Corrigendum

The paragraph before the last in the Editorial in Volume IX, No. 3 of ESD begins with the sentences "Finally, this issue marks a transition in ESD. Gautam Dutt joins the journal as the new Technical Editor, replacing K. Krishna Prasad who bore this responsibility from the very beginning of the journal until his recent retirement." The text should read "Finally, this issue marks a transition in ESD. Gautam Dutt joins the journal as the new Technical Editor. He takes over editorial responsibility from Amulya Reddy, who became de facto Editor when K. Krishna Prasad, who was Editor from the very beginning of the journal, started a process of retirement in 2002."

– Publisher