

# SUPERFICIAL VELOCITY - THE KEY TO DOWNDRAFT GASIFICATION<sup>1</sup>

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## ABSTRACT

The “superficial velocity” (hearth load) of a gasifier is the most important measure of its performance, controlling gas production rate, gas energy content, fuel consumption rate, power output, and char and tar production rate.

The superficial velocity, SV, of a gasifier is defined as:

$$SV = \text{Gas Production Rate} / \text{Cross Sectional Area} = (\text{m}^3/\text{s}) / (\text{m}^2/\text{s}) = \text{m/s}$$

It is easily estimated or measured by measuring gas production rate or fuel throughput and gasifier dimensions. It controls the rate at which air, then gas, passes down through a gasifier. This in turn exercises a primary effect on heat transfer around each particle during flaming pyrolysis of the volatiles, combustion of the tars and gasification of the charcoal.

A **low** SV causes relatively slow pyrolysis conditions at around 600°C, and produces high yields of charcoal - 20-30%, large quantities of unburned tars, and a gas with high hydrocarbon content and high tar (volatile) content. A **high** SV causes very fast pyrolysis, producing less than 10% char-ash at 1050 C and hot gases at 1200-1400 C in the flaming pyrolysis zone. These gases then react with the remaining char-ash to yield tars typically less than 1000 ppm, 5-7% char-ash and a producer gas with less energy.

These relationships have been investigated in a velocity controlled inverted downdraft gasifier with a 7.5 cm diameter. As the superficial velocity was varied from 0.05 m/s to 0.26m/s , the gas production rate increased from 102 to 679 cm<sup>3</sup>/s, charcoal production decreased from 13.0% to 4.7% and tar in the gas decreased from 8330 to 300 mg/kg (ppm).

At low Superficial Velocities (and low Biot numbers), the particles are heated slowly to pyrolysis temperature and remain essentially isothermal. At high superficial velocities the outside of the particle can be incandescent (> 800°C) while the center is still at room temperature. This permits the escaping gases to react with the charcoal, thus reducing the charcoal yield and increasing the gas yield. We call this phenomenon “simultaneous pyrolysis and gasification”, SPG and believe that it is the fundamental reason why the Superficial Velocity controls all other aspects of gasification.

In producing heat the “tars” in producer gas are a useful fuel, providing no cold surfaces intervene. The “inverted downdraft” stoves provide potentially simple, clean cooking for developing countries. At low SVs they also produce charcoal. In producing electric power, tars are detrimental to engine operation, and so high SVs must be maintained to minimize tar and char production.

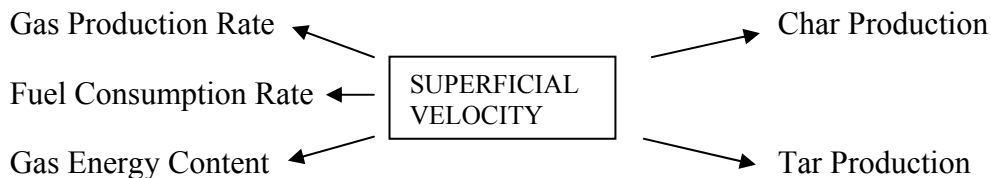
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## Introduction

Clean cooking and distributed power are the major problems of half the world population. Gasification of biomass can help provide solutions to both these problems; unfortunately very little fundamental research has been done on gasification and most new designs are made “by guess and by golly”. Over a million vehicles used gasified biomass successfully during World War II. Since then there have been many attempts to gasify biomass, most unsuccessful.

Biomass gasifiers can be divided into three main categories depending on the source of heat for pyrolysis: **Charcoal burning gasifiers** (updraft, counter-flow ...); **tar burning gasifiers** (downdraft, inverted downdraft, crossdraft, co-flow, open top, topless, ...); and **fluidized bed** (with some char, some tar burning and many varieties). Due to the very high volatile content of biomass, the tar burning gasifiers are preferred when it is necessary to produce a very clean gas for power generation. This paper deals primarily with tar burning gasifiers, but many of the principles can be applied to other forms.

The “superficial velocity”, SV, of a gasifier is the most fundamental measure of the expected behavior of a gasifier and controls most of the other aspects of gasifier operation as shown here:



It is as important to gasifiers as engine rpm to an engine designer or metabolism rate to a physiologist.

It is defined as:

$$SV = \text{Gas Production Rate} / \text{Cross Sectional Area} = (\text{Nm}^3/\text{s}) / (\text{m}^2/\text{s}) = \text{m/s}$$

(It is sometimes defined as the “Hearth load”,  $B_h$  measured in  $\text{Nm}^3/\text{cm}^2\text{hr}$ .  $B_h = 0.36 \text{ SV}$ .)

It is independent of gasifier size, and so permits comparison of gasifiers of very different dimensions. It is easily estimated or measured from air/oxygen fuel throughput and gasifier dimensions. It controls the rate at which air, then gas, passes through a gasifier. This in turn exercises a primary effect on heat transfer around each particle during flaming pyrolysis of the volatiles, on combustion of the tars and the on the degree of gasification of the charcoal. While the SV is the most important measure of performance for design, it is not generally recognized or discussed.

## 1. HISTORICAL

In the book, “Gengas”<sup>1</sup> G. V. Nordenswan says:

“The concept of hearth load plays a very important role in dimensioning a wood gas generator hearth. The hearth load is the quantity of prepared gas, ... divided by the smallest

passage area of the hearth. Thus the hearth load is dimensionally a velocity...”. He goes on to say that the practical range for SV is 0.8m/s (where tars are quite high) to 2.5 m/s (above which charcoal dusting is unacceptable). These numbers only apply to constricted hearth (Imbert) gasifiers. Table 5-2 in Ref. 2 gives design parameters for various Imbert gasifiers ranging from 4 Nm<sup>3</sup>/hr to 230 Nm<sup>3</sup>/hr.

More recent gasifiers would have other values of SV as shown in Table I.

**Table I – Reported Superficial Velocities in various gasifiers<sup>2</sup>**

<b>GASIFIER TYPE</b>	<b>PYROL. ZONE SV m/s</b>	<b>CHAR ZONE SV m/s</b>
<b>Imbert</b>	0.63	2.5
<b>Biomass Corp.</b>	0.24	0.95
<b>SERI Air</b>	0.28	0.28
<b>SERI Oxygen</b>	0.24	0.24
<b>Syn-Gas air</b>	1.71.	1.71.
<b>Syn-Gas oxygen</b>	1.07	1.07
<b>Buck Rogers (Chern)</b>	0.23	0.23
<b>Buck Rogers (Wallawender)</b>	0.13	0.13

The values in Table I are taken from literature reports and generally represent the highest values reported there. The Stratified Downdraft gasifier has the same values of SV in the pyrolysis and char zones since it uses a constant diameter gasification tube. Note that the values differ widely from those recommended for Imbert gasifiers.

## **2. EXPERIMENTAL**

### **4.1 Apparatus**

The apparatus shown in Figure 1 has been built to measure the superficial velocity over a wide range in batch inverted downdraft gasification. (It can be configured with minor modifications to operate in the conventional downdraft mode.) The apparatus is well insulated with pressed fiber refractory (riser sleeve) to minimize heat loss. The air supply is measured with a calibrated flowmeter and the pressure drop, temperature, and gas composition, are measured during the runs.

In use the cylinder is filled with fuel to the gas outlet. The runs reported here were made on mixed +1/4, -1/2 inch hardwood chips with a moisture content of 6.1% wet basis. The top

chips are saturated with alcohol and ignited and the cap is put on. The temperature and pressure drop are monitored as a function of time.

The gas from the gasifier passes through the collection train shown in Figure 2. The outlet pipe is heated with a torch to prevent tar condensation at startup. The gas then passes through a condenser in an ice bath to cool the gas and remove most of the moisture and tar. At the end of the run the moisture recovered was measured and the condenser was rinsed with acetone to collect the majority of the tar. Residual moisture and tar can be removed after the condenser and total gas flow can be measured with a gas meter at the exit and the gas can be flared.

Tars were also measured using a filter to draw aliquot portions directly from the gasifier during the runs. These results and new methods will be reported later. After the run the amount of charcoal remaining was measured.

While the experiments were performed on an “inverted downdraft” gasifier, it is believed that the results will be similar for conventional and new downdraft gasifiers. Further experiments are planned.

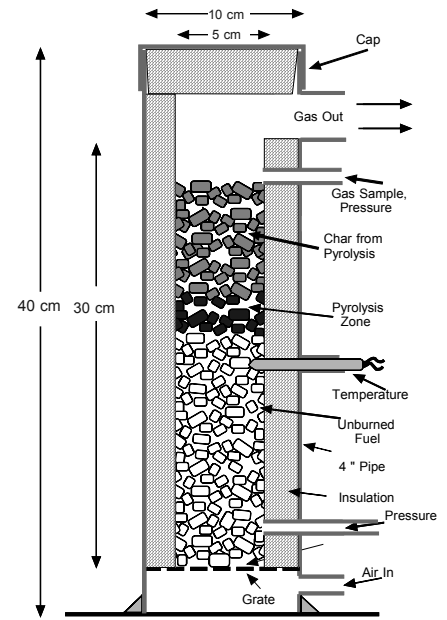


Figure 1 – Gasifier for measuring effects of superficial velocity change.

### 3. RESULTS

The results of these measurements at four SVs are shown in Fig. 3 and reported in Table II

#### 4.1 Flaming Pyrolysis

Tar burning gasifiers consume the tars by a process we call “flaming pyrolysis.”<sup>2</sup> The combustion of pyrolysis products in air in sufficient supply (as in a match) is termed “flaming combustion”. We apply the term “flaming pyrolysis” to the combustion of the same volatiles in an inadequate supply of air so that the products are largely CO and H<sub>2</sub> rather than CO<sub>2</sub> and H<sub>2</sub>O.

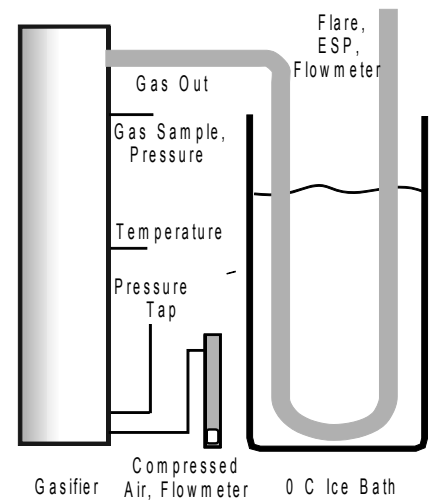


Fig. 2 - Gas Train

## 4.2 Charcoal and Tar Yield

It is seen in Table II and Figures 4 and 5 that charcoal and tar yields depend strongly on the superficial velocity. The reduction in charcoal and tar with increasing SV is due to the increased temperature during pyrolysis shown in Figure 3 and Table II. Tars were measured both by total condensate in the condenser and by use of an absolute filter method.<sup>3</sup>

## 4.3 Air/Fuel ratio

It is obvious in Table II that many other variables depend on SV. In Table II it can be seen that the air/fuel ratio increases from 1.44 to 5.21 as more and more of the charcoal is gasified and the process approaches complete combustion.

**Table II – Results of operation of gasifier at 0.05, 0.19, 0.26 and 0.44 m/sec SV**

Run #	5	6	8	9
<b>MEASURED VALUES</b>				
Air Flow - l/m	4.1	18.8	26.0	46.4
Initial Fuel (g)	89.1	91.1	82.2	84.2
Final Charcoal (g)	11.6	6.8	3.8	0
Condensate (g)	16.7	13.8	11.8	13.8
Tar + Particulate – (g)	2.044	1.463	0.44	0.189
Average Pressure Drop – iwc	0.025	0.11	0.15	0.33
Time of Run – min	33.5	14.4	9.5	8
Pyrolysis Temp	770	993	1033	1045
Pyrolysis time – min	1.0	1.0	0.6	0.6
<b>DERIVED VALUES</b>				
Superficial Velocity - m/s	<b>0.052</b>	<b>0.187</b>	<b>0.260</b>	<b>0.437</b>
Gas Produced – kg (m3)	0.206	0.423	0.387	0.548
Gas production rate – cm3/sec	102	489	679	1141
Tar, Particulate in Gas - mg/m <sup>3</sup>	9941	3460	1138	346
Tar – mg/m <sup>3</sup> -Filter Method	8330	1330	300	10
Fuel Velocity - cm/min	1.20	2.08	3.16	3.75
Air/Fuel Ratio	1.44	3.80	3.47	5.21
Charcoal Yield - %	13.0%	7.5%	4.7%	0.0%

## 4.4 Gas Quality

The gases have not been analyzed. However, it is expected that the energy content will be very high at low superficial velocities (pyrolytic gas) and progress to lower values as more and more of the charcoal is consumed.

## 4.5 Reaction velocity

The flaming pyrolysis gasification reaction in solids is analogous to the combustion of a gas and proceeds at a finite rate. In steady state gasifiers the fuel is consumed at the same rate as the reaction progresses, so fuel flow velocity is identical to reaction velocity. In the batch gasifier studied here the gasification reaction proceeds through the solid bed of fuel and the time required to pyrolyse all the fuel gives the reaction velocities of 1.2 to 3.8 cm/min.

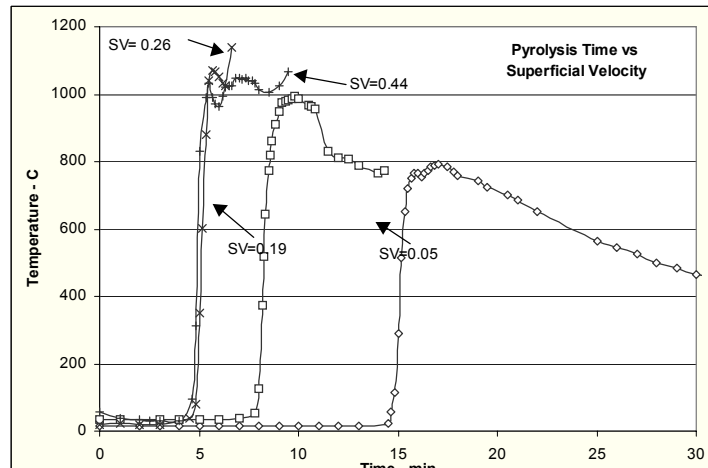


Figure 3 – Temperature Vs time for 4 sample runs

## 4.6 Gasification-Combustion

Gasification can be viewed as a partial combustion reaction, and the declining energy content of the gas and the increasing air fuel ratio suggests that there may be a continuum

between pure pyrolytic gasification, producing gas and charcoal, and pure combustion at high enough air/fuel ratios.

Run 9 produced no charcoal and was probably close to complete combustion. Gas measurements are in progress and will be reported separately.

## 4.7 Time for Pyrolysis

The time required for pyrolysis to charcoal plus volatiles depends on the heat transfer rate and the amount of charcoal produced.

The time for pyrolysis shown in Table II is taken as the time necessary for the first rapid temperature rise shown in Figure 3. It is remarkably short, 0.6 to 1 minute for these chips. We were surprised that there was not a steeper rise time at higher superficial velocities. We believe this can be explained by the less complete pyrolysis at lower velocities.

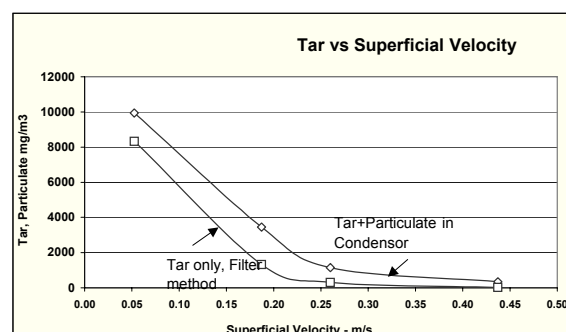
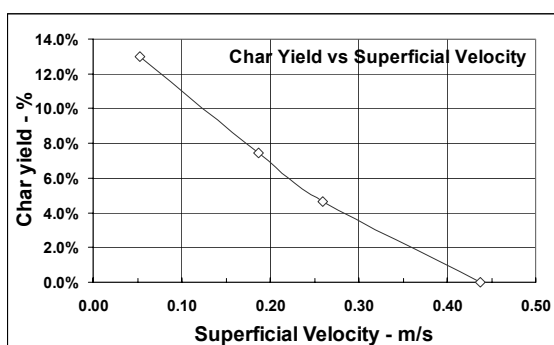


Figure 4- Charcoal yield Vs SV

Figure 5 – Charcoal yield Vs SV

## 4. SIMULTANEOUS PYROLYSIS AND GASIFICATION, SPG

In an earlier paper<sup>4</sup> we described the rapid pyrolysis of single particle birch dowels 3/8-3/4 in diameter in a high temperature gas flame. We noticed that the charcoal yield was 3.1-11.7% rather than the 20-25% yield characteristic of slow pyrolysis. We also measured a heat for pyrolysis of 2.9-3.4 kJ/g, much higher than the 1.8-3 kJ/g required for slow pyrolysis.

We now believe that this is due to “simultaneous pyrolysis and gasification”, SPG. In **slow pyrolysis** the particle remains close to isothermal and the surface temperature does not exceed 400-700°C, not high enough for char gasification reactions. However, with **fast pyrolysis** at higher heat transfer rates, the particle surface temperature can exceed 1000 °C while pyrolysis is continuing at the cool core. In this case the exiting gases and volatiles must pass through the surface charcoal and can react to gasify the charcoal and crack the volatiles. Since these are endothermic reactions, it is not surprising that the heat for pyrolysis is so high. **We believe SPG is the root cause of reduced tar and charcoal at high superficial velocities.** It also explains the success of downdraft gasification in eliminating tars.

## 5. IMPLICATIONS FOR GASIFIERS FOR POWER AND STOVES

We said at the beginning of this paper that clean cooking and power were the primary needs of half the world. A great deal of progress is being made today in gasification for both stoves and power. Much of this work is reported on the Internet. In particular there are continuing forums on both stoves and gasification at [www.crest.org](http://www.crest.org).

### 4.1 Gasifier Stoves

Recently there has been a great deal of interest in cooking for developing countries. Wood cooking is inherently inefficient and dirty, but wood-gas can be burned like propane or natural gas to give fast, clean cooking. The inverted downdraft gasifier is a batch process in which a vessel of biomass is ignited at the top and produces a gas as the pyrolysis reaction proceeds to the bottom. This gas can then be mixed with air and burned much more cleanly than in conventional wood cooking. This can be operated with natural draft<sup>5</sup> or forced draft<sup>6</sup>. The apparatus described here is useful for characterizing biomass gasification at these very low SVs.

### 4.2 Power Gasifiers

The operation, cost and complexity of power gasifiers is very dependent on the tar produced. It is obvious from Figures 4 & 5 that one should operate a gasifier at as high a superficial velocity as possible, consistent with producing a combustible gas, corresponding to 0.26m/s on Figure 3 but not as high as 0.44m/s for these wood chips. We plan to operate this gasifier with different fuels & moisture contents to characterize the optimal velocities for producing gas. Power gasifiers are usually operated in the downdraft mode, but can also be

operated tar-burning updraft.<sup>7</sup> The apparatus described here is useful for investigating the various factors affecting power gasifiers at high SV.

## **6. ACKNOWLEDGEMENTS**

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