PERFORMANCE ANALYSIS OF A COMBINED UPDRAFT-STRATIFIED DOWNDRAFT (CUSD) GASIFIER

by

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ABSTRACT

The performance of the CUSD experimental gasifier was analyzed. The experimental was conducted at the Mechanical Engineering (M.E.) Power Laboratory, College of Engineering, University of the Philippines, Diliman, Quezon City

With the use of ipil-ipil wood chips as fuel, the CUSD gasifier was proven to have a favorable performance as evidenced by the heating value of the gas, color of the flame, specific gasification rate and gasification efficiency. The peak efficiency was obtained at $L = 0.15$ which corresponds to an airflow ratio (downdraft/updraft) of 7.34.

The CUSD gasifier possesses some desirable features which give it advantages over single-stage forced-draft gasifiers. These features include continuous gas production during fuel feeding, stable reaction zones even without tuyeres and movable grate, clean gas being produced with the proper combination of downdraft and updraft airflow rates, and effective removal of ash even without a movable grate. If translated into the user's benefits, these features could mean lower initial investment cost, easier maintenance and simpler operation than existing designs.

INTRODUCTION

Biomass gasification was one of the energy conversion processes revived in the early seventies as an answer to the oil crisis. The common uses of gasifiers are for running engines and for direct heat.

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However, the potential uses of biomass gasifiers are not maximized partly because of operational problems with existing designs. Among such problems are low carbon conversion, the tarry nature of the gas produced and difficulty of feeding fuel to a system while it is in operation.

Downdraft gasifiers which are known to produce clean gas from uncarbonized biomass fuels are not capable of converting all the carbon into gas. Stationary downdraft gasifiers also require a moving grate to remove the char residue even if the fuel used may be low in ash content. Updraft gasifiers are capable of completely converting the solid fuel to ash; however, they produce very dirty gas if uncarbonized fuels are used, pose problems in the gas conveyance and burner systems, and cannot convert the moisture in the fuel (inherent and chemical water) into H_2.

Various configurations have been proposed to improve the performance of fixed-bed gasifiers. One of them is the stratified downdraft gasifier which is a modification of the conventional downdraft reactor (Reed and Levie, 1984; Reed and Markson, 1983; Wallawender and Chern, 1982). Susanto et al. (1982) conducted experiments on the recycling of pyrolysis gas within the reactor. The authors report that the amount of tar was significantly reduced by the process. Some modifications of the updraft design were studied for direct heat applications (Payne et al., 1981; Payne, 1986). A modification of the downdraft reactor is the channel gasifier studied by Richey (1985). The design was conceived to overcome the problem of scale-up that occurs in cylindrical gasifier designs. Cruz (1985) discussed several modifications for fixed-bed gasifiers to facilitate tar-cracking in the reactor. These are the double-shaft gasifier, double-fire gasifier and gasifier with injection of pyrolysis products.

Objective of the Study

The objective of this study is to conduct a performance analysis and establish the operating characteristics of a CUSD gasifier.

Time and Place of the Study

This study was conducted at the College of Engineering, University of the Philippines, Diliman, Quezon City from February 14, 1988 to February 15, 1989.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Technical Description of the CUSD Gasifier

The CUSD gasifier was discussed in three previous papers (Vinluan, 1986; Vinluan, 1987; Vinluan, 1989). This type of gasifier is shown schematically in Fig. 1. The processes that possibly occur inside the gasifier are presented in Fig. 2. Technically, the CUSD is composed of two gasifiers one on top of the other. In the downdraft stage (SD), the fresh fuel undergo

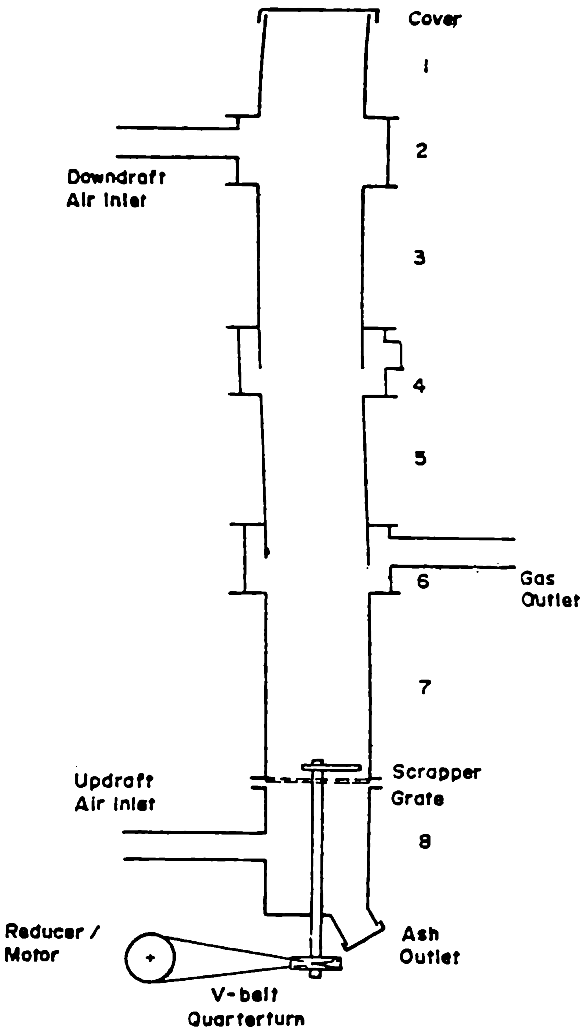

Fig. 1 - Cross-section of the CUSD Gasifier

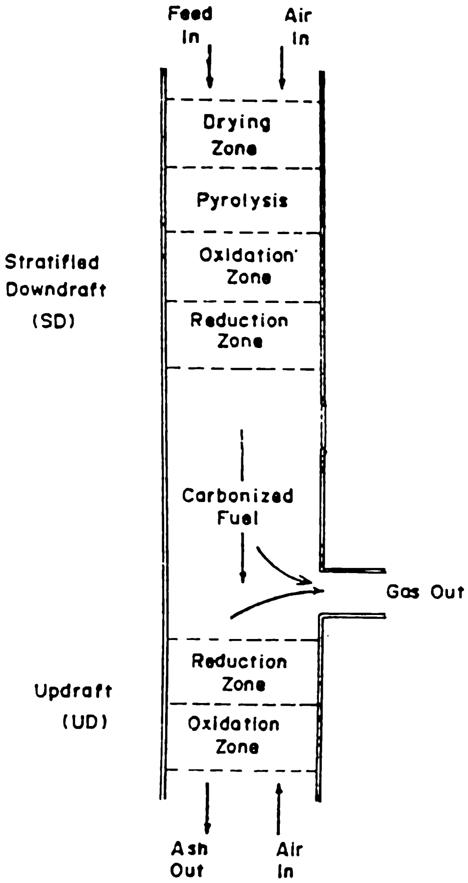

Fig. 2 - Schematic Diagram of a Combined Updraft-Stratified Downdraft (CUSD) Gasifier

downdraft gasification, thus producing a relatively clean gas. In the next stage carbonized fuel which pass through the downdraft stage undergo updraft gasification.

Air is supplied from an electric centrifugal blower and conveyed to the gasifier reactor by pipes 8 cm. in diameter. Air entering the reactor is measured by a square-edged orifice installed in each pipe inlet. The lowermost section in the reactor serves as the ash bin. Inside the ash bin is a removable fixed grate which is secured by supporting pins embedded in the inner side of the ash bin. The grate is fabricated of 12.70 mm (1/2 in.) square bars.

There are two gas outlets in the reactor. In most of the runs, however, only the lower outlet was used. B. I. pipes 8 cm. in diameter and 15 cm. in length were welded to the reactor.

The Fuel

Ipil-ipil (Leucaena leucocephala) wood chips were used as fuel in the gasification experiments. Fuel samples were analyzed at the U.P. Chemistry Laboratory. The properties of the fuel are presented in Table 1.

TABLE 1

PROPERTIES OF THE IPIL-IPIL WOOD CHIPS

Bulk density	0.188 gm/cm3
Average moisture content, dry basis	7.0 percent
Average dimension of chips:	
Length	5.72 cm.
Width	3.32 cm.
Height	1.42 cm.
Proximate analysis (moisture-free basis):	
Volatile	76.42
Fixed carbon	22.64
Ash	0.94
Gross heating value (moisture-free)	-18,943 kJ/kg

Generation of the Theoretical Data Using the CUSD Mathematical Model

The CUSD mathematical model was used to generate the theoretical data. The derivation of the model is discussed in detail in the work of Vinluan (1989). The use of the model was facilitated by defining a variable L, the hypothetical kmole of fixed carbon remains in 1 kmole of biomass as it passes through the downdraft stage.

Testing Procedure

The airflow setting corresponding to the different L-values are presented in Table 2. These ratios were calculated with the use of the CUSD mathematical model. The gasifier was

TABLE 2

RELATIONSHIP BETWEEN THE L-VALUE AND THE AIRFLOW RATE DERIVED FROM THE MATHEMATICAL MODEL

L - value	Theoretical Airflow Ratio[1] Downdraft/Updraft	Experimental Airflow Rate[2] SCM/Hr (Cm. of Water)[3] [Superficial Velocity, Cm/sec]	
		Downdraft	Updraft
0.0		23.50 (2.0) [20.13]	0 (0) [0]
0.15	7.43	23.50 (2.0) [20.13]	3.20 (0.10) [2.74]
0.20	2.90	23.50 (2.0) [20.13]	7.92 (0.25) [6.78]
0.30	1.66	23.50 (2.0) [20.13]	14.52 (0.75) [12.440]
0.40	1.00	23.50 (2.0) [20.13]	23.56 (2.0) [20.13]

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1 - Calculated using the mathematical model.

2 - Airflow adjustments used in the experimental runs.

3 - Fro 1" orifice plate.

fired by dropping burning wood or charcoal to the bottom of the reactor. Wood chips were afterward loaded to the reactor until the reactor was full. Initially, a non-combustible gas was generated. However, after 10-15 minutes a combustible gas was produced, as evidenced by the stable flame in the furnace. The reactor was refilled with fuel by unlocking and opening the cover. After each refueling the cover was put back into position. The process was done without shutting off the blowers or closing the control valves. The gasifier was left to operate continuously for 1 to 1.5 hours, after which gas sampling and other data collection were done.

The sample was collected in a bend near the tip of the outlet pipe. The gas was conveyed from the sampling point to the 500 ml gas sampling bottles by means of copper and rubber tubings. The gas samples were analyzed in the Gas Chromatograph (Shimadzu Model GC-6AM) of the Chemical Engineering Laboratory of the U.P. College of Engineering. Helium and argon were used as carriers in the analyses.

RESULTS AND DISCUSSION

The Experimental and Theoretical data.

Shown in Figures 3, 4, 5 and 6 are the experimental and theoretical values of the components CO, H_2, CO_2 and CH_4, respectively, of the combined gas at different L-values. The experimental CO content for L = 0.0 (pure downdraft) to L=0.3 are within the range 16-20 percent with the highest at L = 0.4. Despite the dispersed behavior of the experimental CO content, the slope of the line connecting the mean values shows an overall similarity to the slope of the theoretical curve. In Figure 4 the highest experimental H_2 values are at L = 0.0 which is a pure downdraft operation. At L = 0.4 where the downdraft and updraft airflow rates are equal, the H_2 content are lowest at 4-7 percent. The values are similar to the observations for updraft wood gasification.

In the succeeding figure the experimental mean CO_2 content at L = 0.0 which ranges from 11-14 percent is slightly higher than the reported values for downdraft gasifiers (Kaupp and Goss, 1981; Reed and Markson, 1983). However, at L = 0.4 the mean experimental CO_2 content is lower than the theoretical value.

The experimental CH_4 content (Figure 6) of the combined gas from L = 0.15 to L = 0.4 are almost constant at about 1.4 percent and equal to the mean CH_4 content at L = 0.0, a pure downdraft operation. This suggests that CH_4 was produced mainly in the downdraft stage, possibly as a product of pyrolysis and not of the methanation reaction.

The plots of the experimental and theoretical cold gas heating values, gasification efficiencies and specific gasification rates (SGR) are shown in Figures 7, 8, and 9.

The highest experimental mean heating values are at L = 0.0 and L = 0.15. The experimental points are within the lower limit of the heating value reported for air gasification of biomass fuels which is in the range of 4,000 - 6,000 kJ/SCM. In Figure 8 the mean experimental gasification efficiency at L = 0.15 is higher than the efficiencies at L = 0.0 (pure downdraft) and at other L-values. For all L-values the specific gasification rate (SGR) varies from a minimum Of 396 kg/m^2-hr (Figure 9). These values are within the lower limit of the report of Kaupp and Goss (1981) on the SGR of downdraft gasifiers which is 225-5,020 kg/m^2-hr; the upper limit applies to gasifiers with throat of constriction. On the other hand, the experimental SGR values are considerably higher than the reported range for updraft gasifiers which is 100-300 kg/m^2-hr. Payne (1986) reported a range for downdraft gasifiers of 500-2,000 kg/m^2-hr.

Analysis of the Gas Production Process in the Experimental CUSD Gasifiers

A situation which deserves close investigation is at L = 0.4 where the downdraft and updraft airflow rates are equal. The combined gas generated a reddish flame when ignited, an indication that a dirty gas is being produced. In contrast, at low L-values (0, 0.15 and 0.2) the gas was clean, as manifested in the bluish color of the flame.

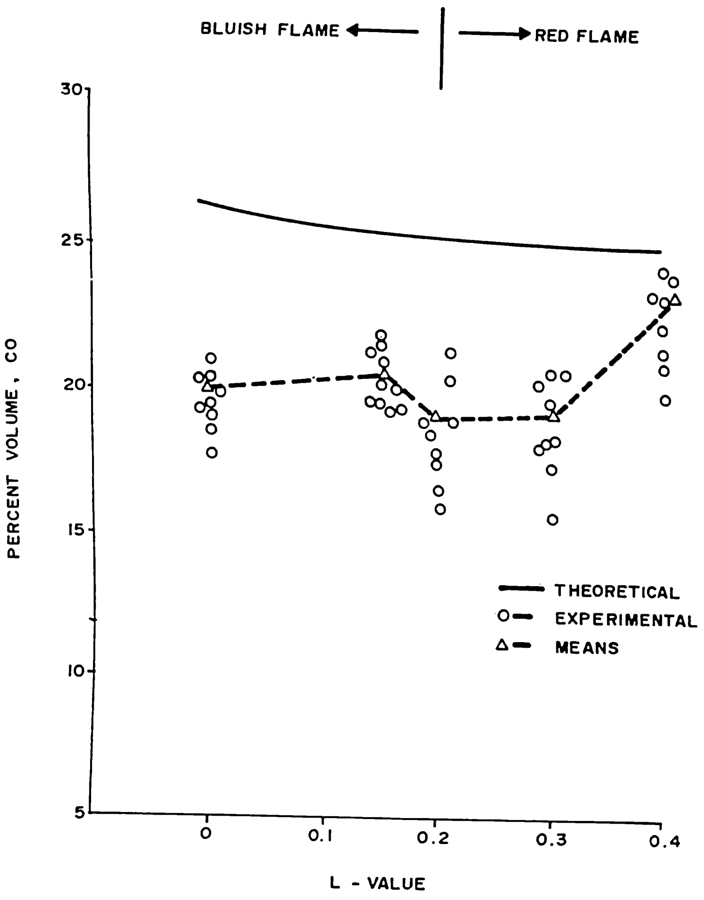

Fig. 3 - The Experimental and Theoretical CO Content of the Combined Gas at Different L-values

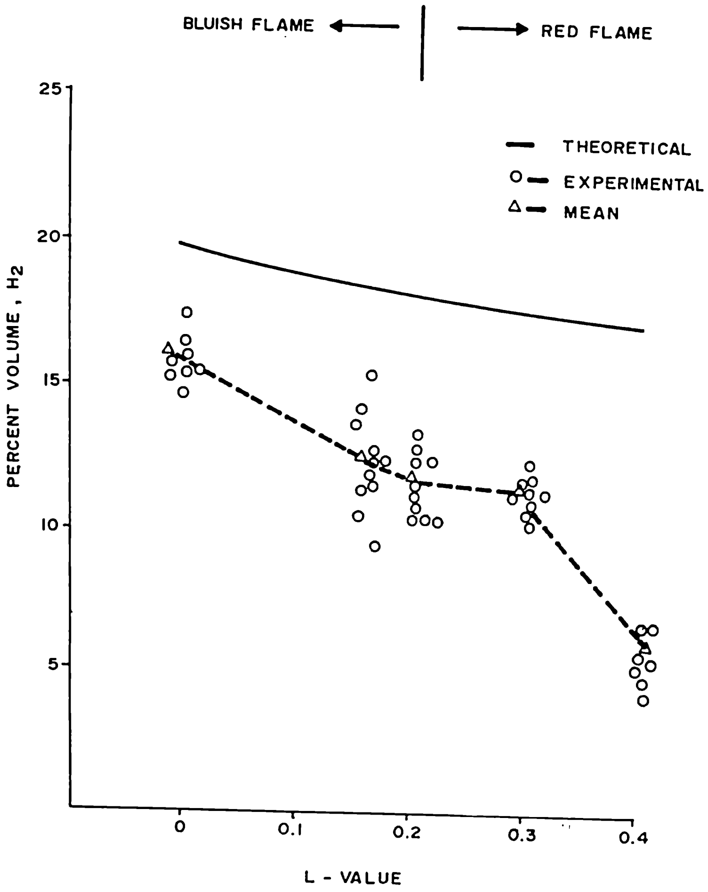

Fig. 4 - The Experimental and Theoretical H_2 Content of the Combined Gas at Different L-values

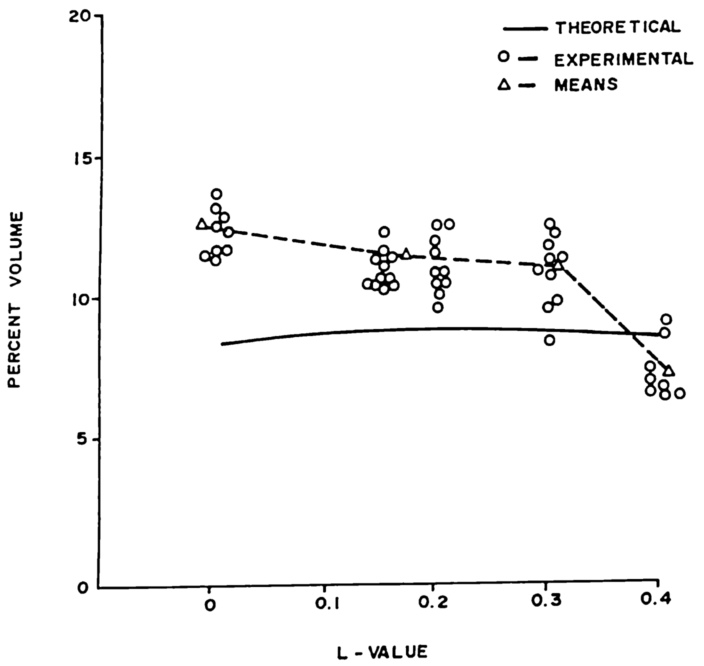

Fig. 5 - The Experimental and Theoretical CO_2 Content of the Combined Gas at Different L- values

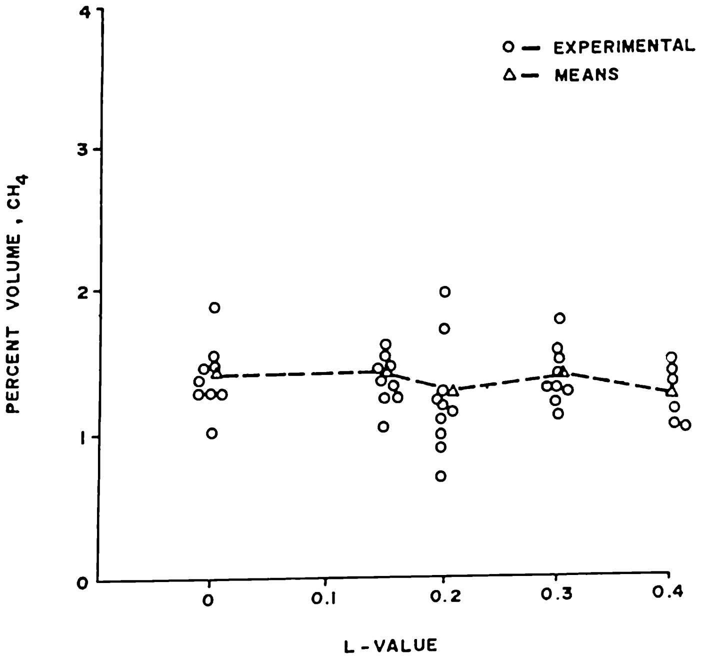

Fig. 6 - The Experimental CH_4 Content of the Combined Gas at Different L-values

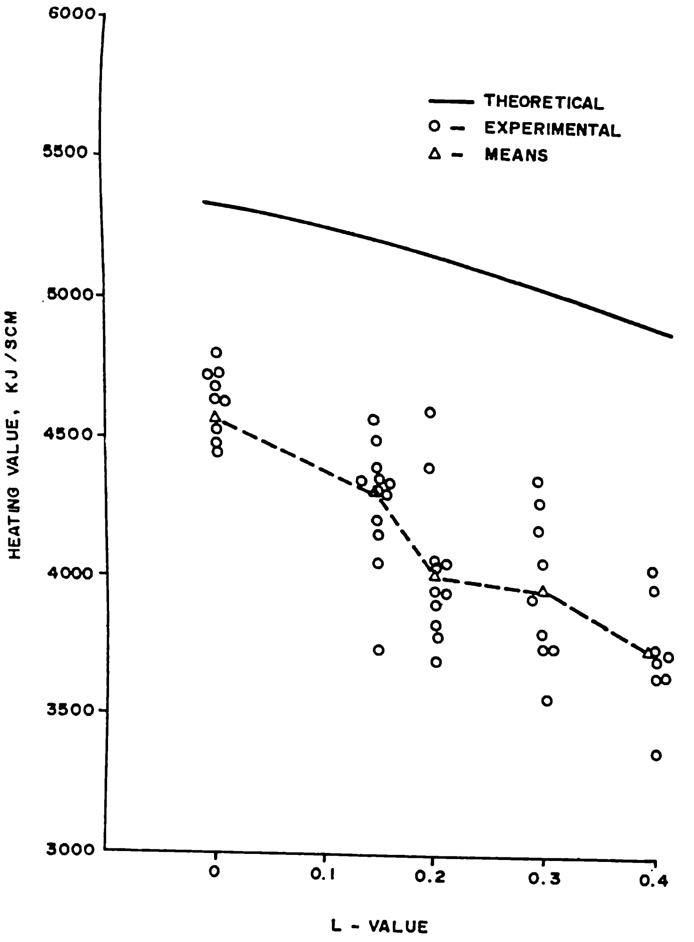

Fig 7 - Comparison of the Experimental and Theoretical Cold Gas Heating Value

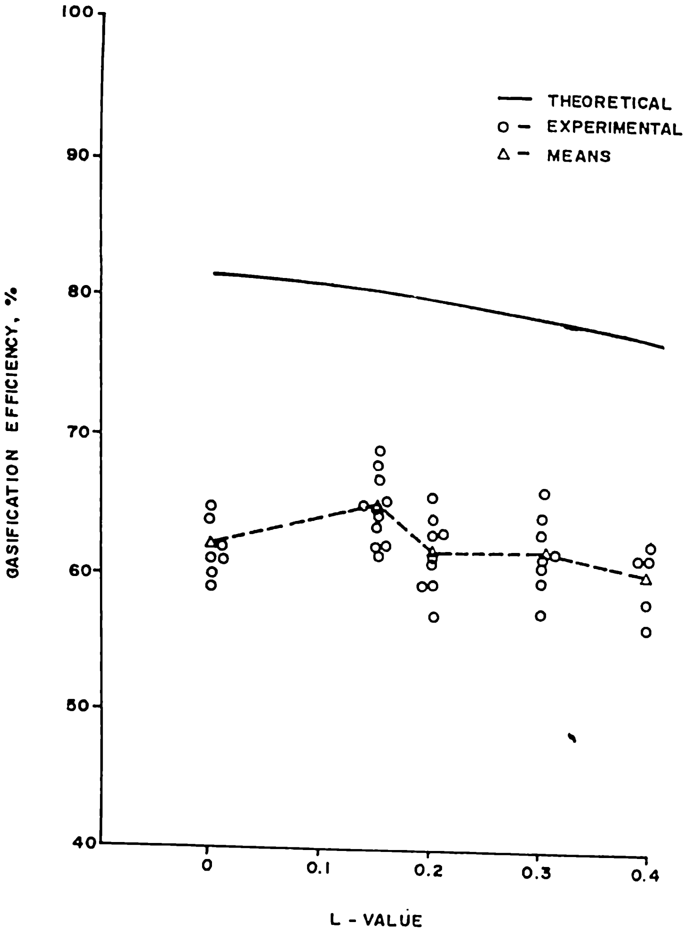

Fig. 8 - Comparison of the Experimental and Theoretical Gasification Efficiency at Different L-values

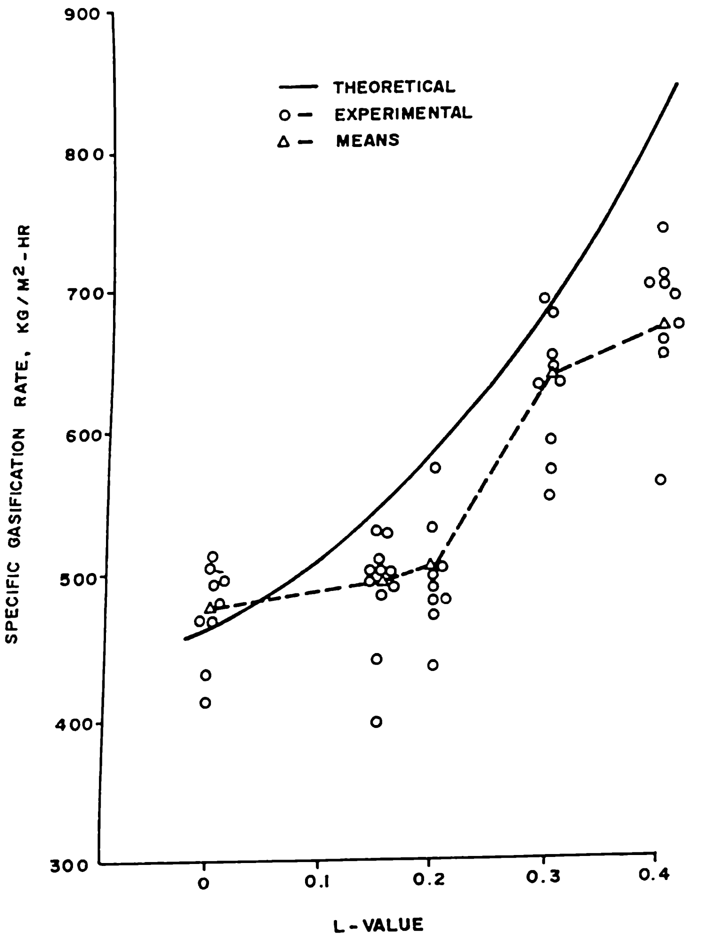

Fig. 9 - Comparison of the Experimental and Theoretical Specific Gasification Rate

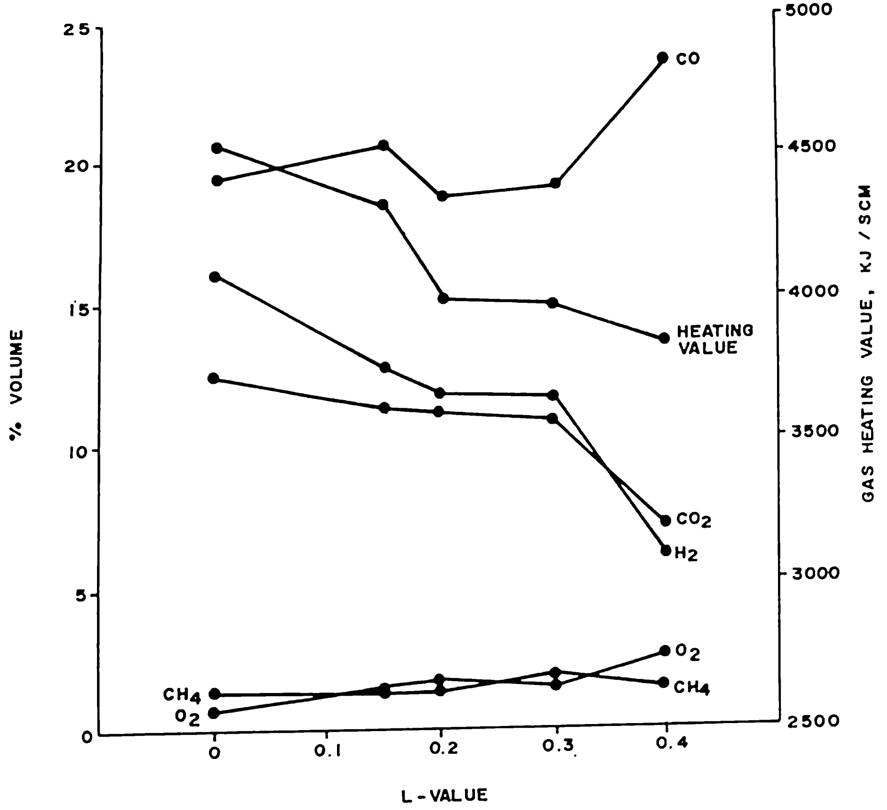

Fig. 10 - The Means of the Gas Components and Heating Value

The production of dirty gas at high L-values could only mean that the downdraft reaction zone was not well established and that the system operated close to a pure updraft reactor. The unstable downdraft reaction zone was possibly due to the fast descent of the bed. This is in turn caused by the volume reduction of the fuel in the updraft stage. The downdraft reaction zone was prevented from sinking because of the pyrolyzing effect of the updraft gas flow to the incoming fuel. The subsequent ignition of a portion of the updraft gas as it mixed with the unreacted O_2 in the downdraft airflow created a very hot zone at the meeting point of the downdraft and updraft gases. The gas produced in the downdraft stage at high L-values was possibly a product of pyrolysis.

The formation of the combined gas is better understood by considering the process in detail. In the downdraft stage the biomass fuel undergo downdraft gasification. The remaining char, apparently without volatiles, goes down to the next stage for updraft gasification. The calculated equilibrium temperature in the updraft stage ranges from 1,135-1,145 ^{o}C for L-values from $L = 0.15$ to $L = 0.4$. With this temperature range and even at 100 ^{o}C lower, the gas composition from the updraft stage is constant.

In contrast, the calculated temperature in the downdraft stage is within the range of 600-700 ^{o}C where the gas composition is highly sensitive to slight changes in temperature. With this in mind, one can infer that the low H_2 content of the combined gas particularly at high L-values (0.3 and 0.4) was mainly due to the instablity in the downdraft stage. This resulted in low conversion of CO_2 and H_2O. It was possibly because of low reaction temperature due to high heat loss in the reactor, and short gas residence time duc to the fast descent of the fuel bed.

The Means of the Experimental Variables

Figure 10 and Figure 11 are the means of the gas components and other experimental variables at different L-values.

In Figure 10, it is shown that the overall slope of the mean CO line increases with the L-values. This is in contrast to the steeply decreasing H_2 line. The behavior of the main combustible components confirms that at high L-values, the performance of the CUSD gasifier approaches that of a pure updraft reactor. However, at low L-values ($L = 0.15$ and $L = 0.20$), the operation is close to a pure downdraft, with the updraft airflow gasifying the remaining char from the downdraft stage.

In Figure 11, the means of the fuel consumption, gas production rate and specific gasification rate are directly proportional to the L-value. The behavior of the curves is expected since an increase in the L-value corresponds to an increase in the airflow rate.

The mean efficiency line has its peak value at $L = 0.15$. The efficiency at $L = 0.0$ (pure downdraft) is almost equal to the efficiencies at $L = 0.20$ and $L = 0.30$; the lowest is at

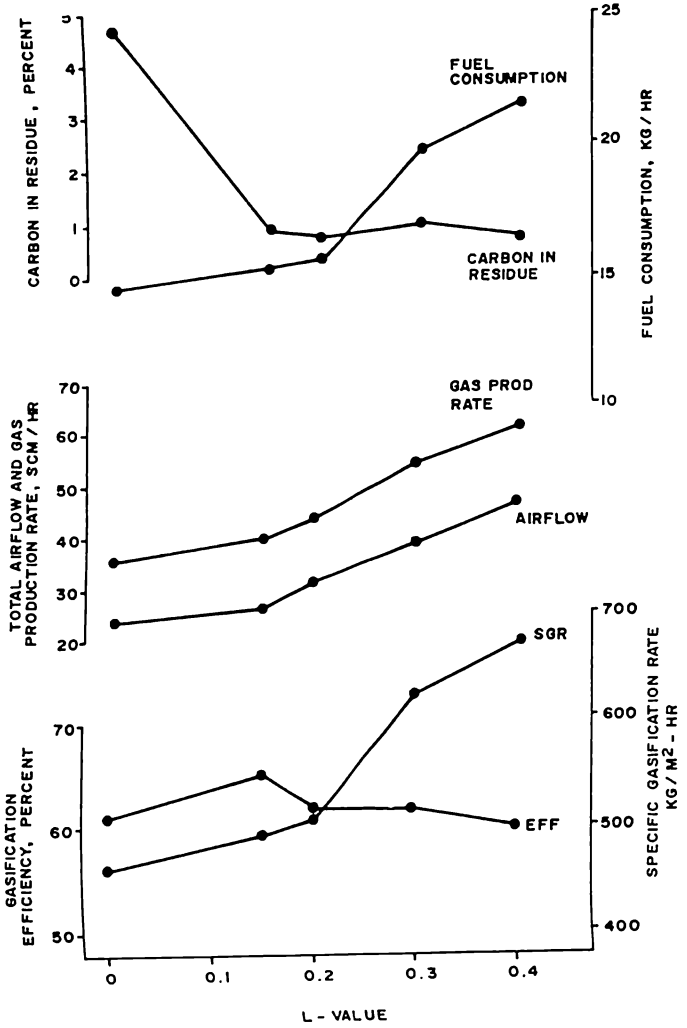

Fig. 11 - The Means of the Experimental Variables

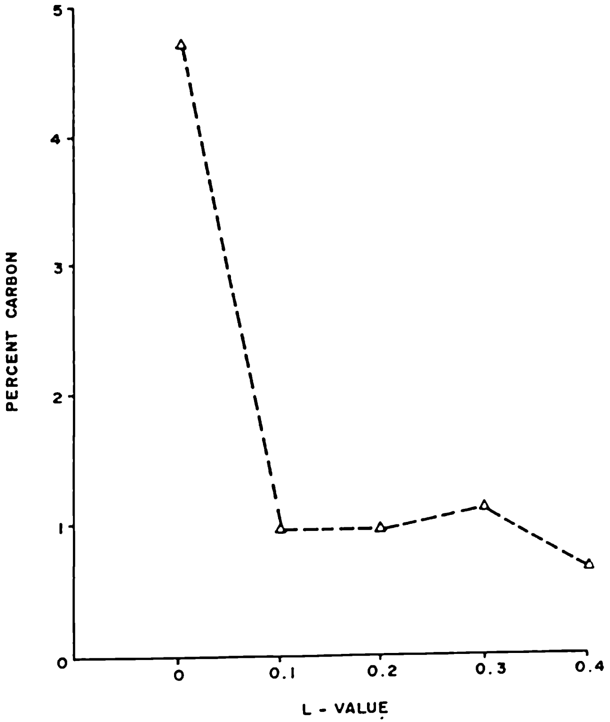

Fig. 12 - Carbon Content of Residue of Different L-values Expressed as Percentage of Ash and Moisture-free Ipil Wood

L = 0.40. The mean efficiency line implies that an increase in the updraft airflow rate, analogous to an increase in L-value, would further reduce the efficiency.

The specific gasification rate (SGR) shows a gradual increase from L = 0.0 to L = 0.2, but an abrupt increases occurs at L = 0.30 and L = 0.40. The line suggests that from L = 0.15, where the peak efficiency occurs, the SGR can be increased but would result to a decreased efficiency.

The carbon content of the residue is also shown in Figure 12. The highest carbon content is at L = 0.0 (pure downdraft) which is 4.7 percent. At other L-values (L = 0.15 to L = 0.40), the carbon content ranges from 0.6 to 1 percent. The average difference between the carbon content of the residue for the pure downdraft (L = 0.0) and for the CUSD modes (L = 0.15 to L = 0.40) is about 4 percent. This seems insignificant but in actual downdraft operation, this amount of char residue could prevent the flow of fuel, and necessitate the use of a rotating grate.

The Attributes of the CUSD Gasifier

In the various runs, several advantages of the CUSD gasifier were observed over conventional fixed-bed (updraft or downdraft) gasifiers. These features include continuous gas production during fuel feeding even without a double-lock system, effective removal of ash even without a movable grate, stable reaction zones even without tuyeres ot rotating grate, and clean gas and higher gasification efficiency with the proper combination of downdraft and updraft airflow rate.

CONLUSIONS

Based on the results of the experiments the following conclusions are presented:

1. With the use of ipil-ipil wood chips as fuel the CUSD gasifier performed favorably, as judged by the heating value of the gas (3,400-4,800 kJ/SCM), color of flame, specific gasification rate (400-740 kg/m^2-hr) and cold gas gasification efficiency (56-69 percent). Peak gasification efficiency was obtained at L = 0.15, which is higher than the efficiencies at L = 0.0 (pure downdraft) and at other L-values.

2. The CUSD gasifier possesses desirable features compared to forced-draft single-stage gasifiers. These features are: (a) continuous gas production during feeding, (b) effective removal of ash even without a movable grate, (c) clean gas produced from the proper combination of downdraft and updraft airflow rates, and (d) higher gasification efficiency than a pure downdraft gasifier.

3. The CUSD gasifier is a potential gasifier for direct-heat applications.

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