Performance Evaluation of a Direct Water-injected Gasifier (DWIG) Utilizing Low-grade Philippine Coals

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I. Introduction

As the population of the world increases, the world's industrial energy requirements also increase. With limited oil reserves and unstable oil prices, the energy users around the world have considered using alternative energy sources, like coal, as industrial fuels. Using coal for the production of fuel gas for use as industrial retrofit fuel in oil-fired thermal units like furnaces, boilers, and kilns, is considered as one of the most promising near-term fuel conversion technologies for non-oil producing countries. The Philippines, which has very minimal oil reserves, is fortunate to have large deposits of coal. Philippine coals however, are mostly low-ranked and on the low-grade category. Some operating problems are usually encountered when these low-grade coals are utilized directly as industrial fuels. The Philippines has a number of oil-fired thermal units that are experiencing difficulties due to high oil prices. The key to making these thermal units more economically viable in their continued operation is to reduce their fuel oil consumption without adversely affecting their production output. The use of low-grade coals and agricultural wastes as augmentation or substitute fuels in these oil-fired thermal units is one of the possible solutions. It will considerably lower the operating costs since these low-grade coals are much cheaper than imported oil. It will also help reduce the country's oil import bill since these materials are locally available.

This study was conducted to evaluate the feasibility of utilizing low-grade and low rank Philippine coals and agricultural wastes as alternative fuel for an existing oil-fired furnace that is retrofitted with an updraft gasifier, a fire chamber, and a replacement gas burner. The fixed-bed gasifier is close-coupled to the furnace by means of a gas burner. The gasifier is provided with a water injector that is used to introduce water directly into itself. The study focuses on the effect of using liquid water instead of steam in gasifying low-grade coals. The direct use of liquid water means that a boiler will not be needed, and this in

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turn means savings in capital and operating costs. The study includes the formulation of a mathematical model and a computer simulation procedure that is used to predict the performance of the experimental set-up using regular coal analyses and a few operational parameters.

II. Objectives of the Study

The main objective of this study is to evaluate the effect of the use of liquid water on the performance of a direct water-injected gasifier. The other objective is to establish the feasibility of utilizing producer gas from indigenous solid fuels particularly low-rank and low-grade Philippine coals, coconut husk and ipil-ipil chips as substitute or augmentation fuel in an experimental gasifier-furnace set-up. Specifically, the study aims to accomplish the following:

1. Study the effect of the use of liquid water, instead of steam, on the gasification of low-grade and low-rank Philippine coals;
2. Study the performance of the experimental gasifier-furnace set-up using low-grade local coals and agricultural wastes as fuels;
3. Develop a mathematical model or a simulation procedure that can predict the performance of the experimental set-up from fuel composition, moisture content, water blast and other relevant factors,
4. Validate the model by comparing its results with experimental data.

III. Theoretical Considerations

Gasification may be defined as a chemical process in which carbon (C) is converted into an inflammable gas, which may consist of different proportions of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), water (H_2O), nitrogen (N_2), and methane (CH_4). The gasification process is attained by the reaction of fuel carbon with a controlled amount of a gasifying agent or an oxidizer. Air and steam are the usual gasifying agents used in gasification. It has been established by numerous studies that the following chemical reactions occur in the process of interaction of carbon with O_2 and H_2O.

$C + O_2 \rightleftharpoons CO_2$	*Combustion*
$2S + O_2 \rightleftharpoons 2CO$	
$2CO + O_2 \rightleftharpoons 2CO_2$	
$C + CO_2 \rightleftharpoons 2CO$	*Boudouard Reaction*
$C + H_2O \rightleftharpoons CO + H_2$	*Carbon-Steam Reaction*
$CO + H_2O \rightleftharpoons CO_2 + H_2$	*Shift Reaction*
$CO_2 + C \rightleftharpoons 2CO$	
$C + 2H_2 \rightleftharpoons CH_4$	*Carbon Hydrogenation*
$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$	
$2CO + 2H_2 \rightleftharpoons CH_4 + H_2$	

If steam as well as air is admitted into the fuel bed of the gasifier, the Boudouard reaction and the carbon-steam reaction will contribute CO and H_2 to the product gas with corresponding greater heat content. In the process of interaction of carbon with steam, hydrogen also reacts with carbon and carbon monoxide to form methane, which also contributes to the enhancement of the quality of the product gas. The Boudouard and carbon-steam reactions are highly endothermic and tend to lower the fuel bed temperature and therefore the combustion temperature will be limited to levels below the ash fusion temperature thereby preventing clinker formation in the gasifier. Lower combustion zone temperature, however, also tends to promote shift reaction thereby raising the CO_2 content of the gas at the expense of CO.

The direct injection of liquid water instead of steam into the gasifier may cause further reaction in the temperature of the oxidation zone due to the latent heat of vaporization of liquid water, which has a cooling effect on the fuel bed. The rate of water addition should therefore be closely monitored and controlled to avoid excessive addition of liquid water, which will promote shift reaction that favors formation of the nonflammable CO_2 at the expense of CO.

IV. Methodology

To achieve the objectives of this study, experiments were conducted at the laboratories of the College of Engineering of the University of the Philippines in Diliman, Quezon City. Additional experiments were also conducted at and at the laboratories of the Energy and Mineral Research Center (EMRC) of the University of North Dakota in Grand Forks, North Dakota, U.S.A.

1. *Laboratory Tests*

Low-grade coals coming from Central Cebu and from the PNOC coal terminal in Calaca, Batangas were used in the study. Coconut husk and ipil-ipil chips were also tested. The determination for the calorific value, proximate analysis, ultimate analysis, ash (x-ray fluorescent) analysis, ash fusibility test, free swelling index test, and thermal analysis were conducted for the solid fuel samples. A Fisher Model 490 Proximate Analyzer was used in the proximate analyses. For the elemental composition, a LECO 600 CHN Analyzer was used for the analyses of the carbon, hydrogen and nitrogen contents. The sulfur content was determined using a Fisher Sulfur Analyzer. The composition of the coal ash was determined using the Kevex 0700 Spectrometer and Kevex 7000 X-ray Analysis System. The heating values were determined using a "PARR" Adiabatic Bomb Calorimeter. Thermogravimetric and thermal analyses were conducted on the fuel samples using a DuPont 951 Thermogravimetric Analyzer interfaced with DuPont 1090 Thermal Analyzer.

2. *Experimental Apparatus and Procedures*

Figure 1 shows the schematic diagram of the experimental set-up used in this study. The set-up consists of a direct water-injected gasifier and an existing oil-fired furnace. The gasifier is a fixed bed, updraft type having a rectangular cross section and measures 0.81 m. × 1.12 m. × 1.83 m. on the outside. The gasifier, which is provided with a fire chamber inside its middle section, is close-coupled to the furnace. One end of the fire chamber is directly connected to the gas burner while the other (opposite) end is connected to the oil burner. The gasifier is fabricated with a double-lock feed hopper at the top through which the solid fuel is introduced.

The experimental unit is designed to operate on both single-fuel and mixed (dual mode) feeding using a solid fuel in the gasifier and with or without oil firing in the fire chamber. In the single fuel mode, coal (or agricultural waste) is fed into the gasifier through the hopper at the top of the gasifier and the gas generated is forced into the gas burner, where it is mixed with air for combustion in the furnace. In the dual fuel feeding, a limited amount of fuel oil is used together with the solid fuel.

At the start of the experiment, the gasifier is filled with small quantities of dried wood chips or charcoals enough to cover the grate surface. The fire is started by dropping burning wood chips or charcoal soaked with kerosene or fuel through the fuel hopper at the top of the initial charge. After the spontaneous combustion occurred, solid fuels to be tested are loaded until the top level of the charge is well above the fire chamber. After about 20-40 minutes a combustible gas is produced. The level of the fuel bed is measured by means of a poking rod inserted through the poke hole. The weight of the fuel being charged into the gasifier and the time the charging was made are recorded. Refueling and fuel measurements are done about 5 times in 1 hour. Based on the difference in fuel level, fuel density and configuration of the reactor, the rate of solid fuel consumption is estimated.

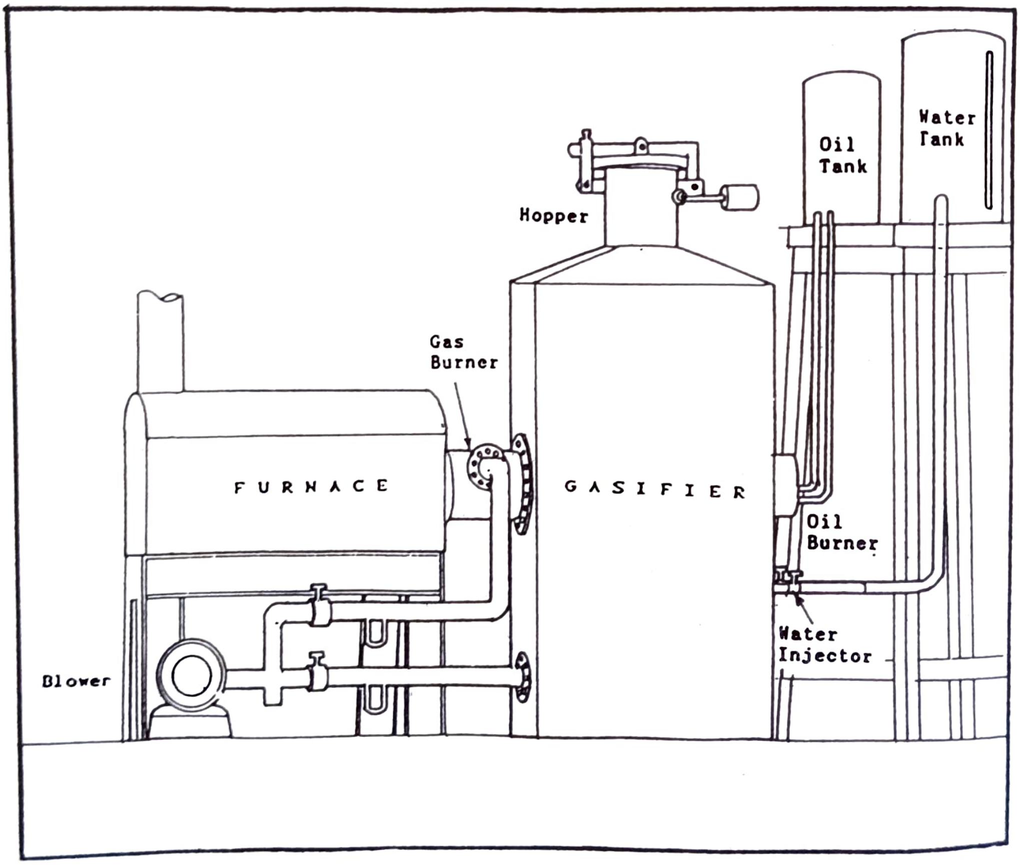


Figure 1 – Schematic Diagram of the Experimental DWIG Gasifier-Furnace Set-up

Additional fuel charge is added to the reactor by unlocking and opening the cover of the fuel hopper. Before opening the top cover the conical lock at the bottom of the hopper is closed first. The top cover is then opened and the hopper is filled with fuel. After each refueling the top cover is put back and locked into position and the conical lock is then opened. The fuel charge moves downward by gravity. Refueling is done without stopping the operation.

After the reactor attains equilibrium, the flow of air is adjusted to the maximum possible rate that can give a good quality gas. A centrifugal air blower supplies the air for gasification in the reactor and the air for combustion in the furnace. Air is introduced into the gasifier by means of a perforated steel pipe located just below the grate. The airflow rate to the gasifier is measured by means of a manometer.

Once the flame in the furnace has stabilized, which is about 1 to 1.5 hours of continuous operation, liquid water is directly added to the gasifier by means of water injectors. These water injectors are made up of perforated steel tubes and are inserted into the gasifier through the water blast holes located above the grate. The injectors are connected to the elevated water tank by means of a flexible hose. The injectors are sealed by means of a gasket to prevent gas leakage. Water from the tank is fed by gravity to the gasifier and water consumption is measured by means of an external water level indicator attached to the water tank. The flow of water is controlled by means of a valve.

Gas samples are collected by means of a flexible tube that is connected to a tube coil immersed in a water tank for cooling. Gas samples from the reactor are conveyed from the sampling point to the sampling bottles by means of cooper tubings and flexible hoses. A Shimadzu Gas Chromatograph (Model GC 6 AM) with digital print outs is used in the analyses of the compositions of the fuel gas and the furnace flue gas samples. Helium and argon are used as carriers in the gas analyses.

3. *The Mathematical Model*

A mathematical model is formulated to predict the performance of the experimental set-up using the regular fuel analyses and a few operational parameters. For the DWIG gasifier, the calculation process in the determination of the gas composition is based on the Gumz model with some modifications. The formulation of the equations for the calculation process is based on the laws of thermodynamics involving mass and energy balances, partial pressures, chemical equilibrium and a few operational parameters. Specifically, the equations are based on the definitions of the equilibrium constants of the Boudouard reaction, of the heterogeneous water-gas reaction, of the methane formation, the law of partial pressures or partial volumes, and the mass balances for carbon, hydrogen, oxygen and nitrogen. These form a set of simultaneous non-linear equations, which is the basis of the calculation process. Also included in the calculation process are the equations for the determination of the reaction, adiabatic, and exit temperatures. The model is written in Turbo Pascal and is designed to run on IBM compatible Personal Computers, which are easy to use and are widely accepted.

The data obtained from the experimental test runs and from the laboratory tests are recorded for analysis with the use of a computer. Comparative analyses of the experimental values and the predicted or simulated results are conducted.

V. Results and Discussion

The proximate and ultimate analyses and the heating values of the two low-grade coals are shown in Tables 1 and 2. From the analyses, the PNOC coal has a calorific value of 11,369 Btu/lb while Cebu coal has a lower heating value of 10,937 BTU/lb as determined. PNOC coal however has relatively high ash content of 22.09% with the sulfur content of only 0.55%. Cebu coal has only 8.40% moisture content and 3.2% sulfur content. The moisture content of the PNOC coal is 1.34% while Cebu coal has 7.63% moisture as determined. The results of the thermogravimetric and thermal analyses shown in the TGA Plots in Figure 2 confirm the results of the proximate analyses. The ultimate analysis shows that the two coals have almost the same carbon content, 65.7% for PNOC and 62.02% for Cebu coal as determined. Tables 3 and 4 show the laboratory analyses for coconut husk and ipil-ipil wood chips, respectively.

Table 1. ***Laboratory Analyses of* PNOC *Coal***

	AS DET. (%)	AS RECD. (%)	MOIST FREE (%)	MOIST /ASH FREE (%)
PROXIMATE ANALYSIS				
Moisture	1.34	2.10	N/A	N/A
Volatile Matter	20.56	20.40	20.84	26.85
Fixed Carbon	56.00	55.56	56.77	73.14
Ash	22.09	21.92	22.39	N/A
ULTIMATE ANALYSIS				
Carbon	65.70	65.21	66.59	5.06
Hydrogen	4.03	4.08	3.93	85.80
Nitrogen	1.55	1.53	1.57	2.02
Sulfur	0.55	0.55	0.56	0.72
Oxygen (by difference)	6.08	6.68	4.95	6.38
Ash	22.09	21.92	22.39	N/A
HEATING VALUE				
Btu/lb	11,369	11,284	11,523	14,847
kJ/kg	26,444	26,247	26,802	34,534

Table 2. ***Laboratory Analyses of Cebu Coal***

	AS DET. (%)	AS RECD. (%)	MOIST FREE (%)	MOIST /ASH FREE (%)
PROXIMATE ANALYSIS				
Moisture	7.63	9.80	N/A	N/A
Volatile Matter	40.31	39.37	43.64	48.00
Fixed Carbon	43.65	42.61	47.26	51.99
Ash	8.40	8.21	9.10	N/A
ULTIMATE ANALYSIS				
Carbon	62.02	60.58	67.14	73.86
Hydrogen	5.68	5.80	5.23	5.75
Nitrogen	1.34	1.30	1.45	1.59
Sulfur	3.24	3.16	3.51	3.86
Oxygen (Ind)	19.31	20.93	13.56	14.92
Ash	8.40	8.21	9.10	N/A
HEATING VALUE				
Btu/lb	10,937	10,683	11,840	13,025
kJ/kg	25,493	24,849	27,540	30,296

Table 3. ***Laboratory Analyses of Coconut Husk***

	AS DET. (%)	AS RECD. (%)	MOIST FREE (%)	MOIST /ASH FREE (%)
PROXIMATE ANALYSIS				
Moisture	8.57	8.60	N/A	N/A
Volatile Matter	64.45	64.45	70.50	72.74
Fixed Carbon	24.15	24.12	26.42	27.25
Ash	2.81	2.81	3.08	N/A
ULTIMATE ANALYSIS				
Carbon	46.30	46.30	50.63	52.24
Hydrogen	5.58	5.58	5.06	5.22
Nitrogen	0.55	0.55	0.60	0.62
Sulfur	0.00	0.00	0.00	0.00
Oxygen (Ind)	44.76	44.76	40.63	41.92
Ash	2.81	2.81	3.08	N/A
HEATING VALUE				
Btu/lb	7,844	7,844	8,579	8,851

Table 4. ***Laboratory Analyses of Ipil-ipil Wood Chips***

	AS DET. (%)	MOIST FREE (%)	MOIST /ASH FREE (%)
PROXIMATE ANALYSIS			
Moisture	8.67	N/A	N/A
Volatile Matter	72.32	79.33	80.98
Fixed Carbon	16.98	18.63	19.02
Ash	1.86	2.04	N/A
ULTIMATE ANALYSIS			
Carbon	47.43	48.32	49.31
Hydrogen	6.18	6.30	6.43
Oxygen	42.59	43.38	44.26
Ash	1.86	2.04	N/A
CALORIFIC VALUE *(Moisture-free basis)*			
Btu/lb		8,172	

Table 5 shows that Cebu coal with a free swelling index of only ½ is practically a non-caking and non-swelling type. PNOC coal has also a low free swelling index of only 1.5. The ash analyses for the local coals, which are presented in Tables 6 and 7, show that both coals have high silica content, 45.4% for PNOC coals and 39.6% for Cebu coal (ash percentage basis).

Figure 3 shows the effect of water on the product gas composition of Cebu coal. The amount of water injected into the gasifier is varied from 0.02 liters per minute to 0.48 liters per minute, which corresponds to a water-to-coal ratio (*wcr*) of 0.05 kg/kg to 1.44 kg/kg. As shown in Figure 3 the percentages of H_2, CH_4, CO_2 in a unit volume of product gas increase with the increase in the water to coal ratio. The percentage of CO on the other hand decreases as the *wcr* values increases.

Table 4. ***Ash Fusion Characteristics and Swelling Properties of Local Coals***

	PNOC Bituminous	**Cebu Subbituminous**
ASH FUSION: (°C)		
Initial Deformation Temperature	1217	1098
Softening Temperature	1257	1136
Hemispherical Temperature	1281	1218
Fluid Temperature	1302	1238
FREE SWELLING INDEX (FSI)	1.5	.5

Figure 4 shows the effect of the direct addition of water on the composition of the product gas generated from the gasification of PNOC coal. The same trend observed in Figure 3 could be observed in Figure 4. The amount of water directly injected into the gasifier was varied which corresponds to the variation of the water to coal ratio from 0.03 kg/kg to 1.33 kg/kg. In this range the H_2, CO_2, and CH_4 contents of the gas increase while the CO content decreases as the *wcr* value increases.

Table 6. ***X-ray Fluorescent Analysis for* PNOC *Coal***

	% AS OXIDES		
	% Elemental	% of Ash	% of Ash (Normal)
Silica	21.240	45.40	46.10
Aluminum Oxide	13.400	25.30	25.70
Ferric Oxide	4.079	5.80	6.30
Titanium Oxide	0.857	1.40	1.50
Phosph. Pentoxide	0.213	0.50	0.50
Calcium Oxide	6.828	9.60	9.70
Magnesium Oxide	1.385	2.30	2.30
Sodium Oxide	0.731	1.00	1.00
Potassium Oxide	0.330	0.40	0.40
Sulfur Trioxide	2.722	6.80	6.90
TOTALS:		98.53	100.00

Table 7. ***X-ray Fluorescent Analysis for Cebu Coal***

	% AS OXIDES		
	% Elemental	% of Ash	% of Ash (Normal)
Silica	18.500	39.60	37.80
Aluminum Oxide	12.400	23.40	22.40
Ferric Oxide	15.620	22.30	21.40
Titanium Oxide	0.882	1.50	1.40
Phosph. Pentoxide	0.092	0.20	0.20
Calcium Oxide	4.634	6.50	6.20
Magnesium Oxide	1.314	2.20	2.10
Sodium Oxide	0.000	0.00	0.00
Potassium Oxide	0.455	0.50	0.50
Sulfur Trioxide	3.339	8.30	8.00
TOTALS:		104.56	100.00

The effects of water (*pwab*) on efficiency (*eff*) and specific gasification rate (*sgr*) are shown in Figure 5 for Cebu coal. Figure 6 shows the effect of water (*wcr*) on the efficiency (*eff*) and specific gasification rate (*sgr*) for PNOC coal. Figure 7 shows the water to coal ratio (*wcr*) versus gasification performance (*efficiency*) for both coals. The peak gasification occurs at the *wcr* value of 0.48 corresponding to about 64.5 % gasification efficiency for PNOC coal. For Cebu coal the peak gasification occurs at a water to coal ratio (*wcr*) value of 0.53 corresponding to about 72.9 % gasification efficiency.

The comparisons of the mathematical and experimental product gas composition results for local coals are shown in Figure 8 for Cebu coal at *wcr* value of 0.53 and Figure 9 for PNOC coal at *wcr* of 0.48. Figure 10 shows the comparison of the experimental product gas compositions of coconut husk and ipil-ipil chips. The comparisons of the experimental and simulation results of the effect of water (*pwab*) on gasifier performance (*efficiency*) are shown in Figure 11 for PNOC coal and Figure 12 for Cebu coal. Comparative results have shown a good agreement between predicted and experimental values. The simulation procedure has also been found to predict the same trend of general behavior, which is observed in the actual operation of the experimental set-up.

VI. Conclusions

The following conclusions are presented based on the results of the actual experiments and computer simulations:

1. The experiments have shown that liquid water can be used instead of steam in preventing clinkering of the ash and also in improving gas quality. For both the Cebu and PNOC coals, the product gas composition is determined primarily by the percentage of water in the air blast (*pwab*) or by the water to coal ratio (*wcr*). As greater amount of water is added, more hydrogen, carbon dioxide and methane are produced and less carbon monoxide is generated. For PNOC coal, peak gasification performance is obtained at a *wcr* of 0.48 kg/kg corresponding to a cold gas efficiency (*eff*) of 64% and a specific gasification rate (*sgr*) of 32.3 kg/sq.m-hr. For the Cebu coal, the peak cold gas efficiency of about 72% and a specific gasification rate of 41 kg/sq.m-hr are obtained at a *wcr* of 0.53 kg/kg. The use of liquid water in gasification requires a relatively simple and less expensive device compared to the used of steam, which requires a separate boiler and therefore more expensive.

2. The two low-grade coals tested have generally gasified well in the experimental set-up as evidenced by the cold gas efficiency (60-64% for PNOC and 66-72% for Cebu), specific gasification rate (31-38 kg/sq.m-hr for PNOC and 36-46 kg/sq.m-hr for Cebu), color of the flame in the furnace and heating

value of the gas (2.8-3.5 MJ/SCM for PNOC and 2.9-3.8 MJ/SCM for Cebu). The bigger size (run-of-mine) Cebu coal performed better as fuel in the set-up compared with the pulverized/stoke-grade PNOC coal as judged by the higher peak cold gas efficiency and the absence of channeling for Cebu coal. Cebu coal, coconut husk and ipil-ipil chips, which have relatively low ash content (2.81% to 9.10%, moist-free), performed better in the fixed-bed gasified compared with the PNOC coal, which has a higher ash content (22.39%, moist-free). The use of the experimental set-up has shown that the oil-fired furnace retrofitted with a gasifier could be operated using dual fuel firing with producer gas and fuel oil. The experiments have demonstrated also that the set-up could be fired using straight (100%) producer gas from the solid fuel.

3. The mathematical model formulated is useful for predicting the performance of the direct-water injected gasifier and the possible improvements on its operations. The model can be used for different ranks and grades of coals and lignites and various compositions of water and oxidant proportions.

4. The mathematical model performed fairly well compared with other experimental and model simulation results. Comparative results have shown a good agreement between predicted and experimental values. The simulation procedure has also been found to predict the same trend of general behavior that is observed in the actual operation of the experimental set-up thereby confirming its validity.

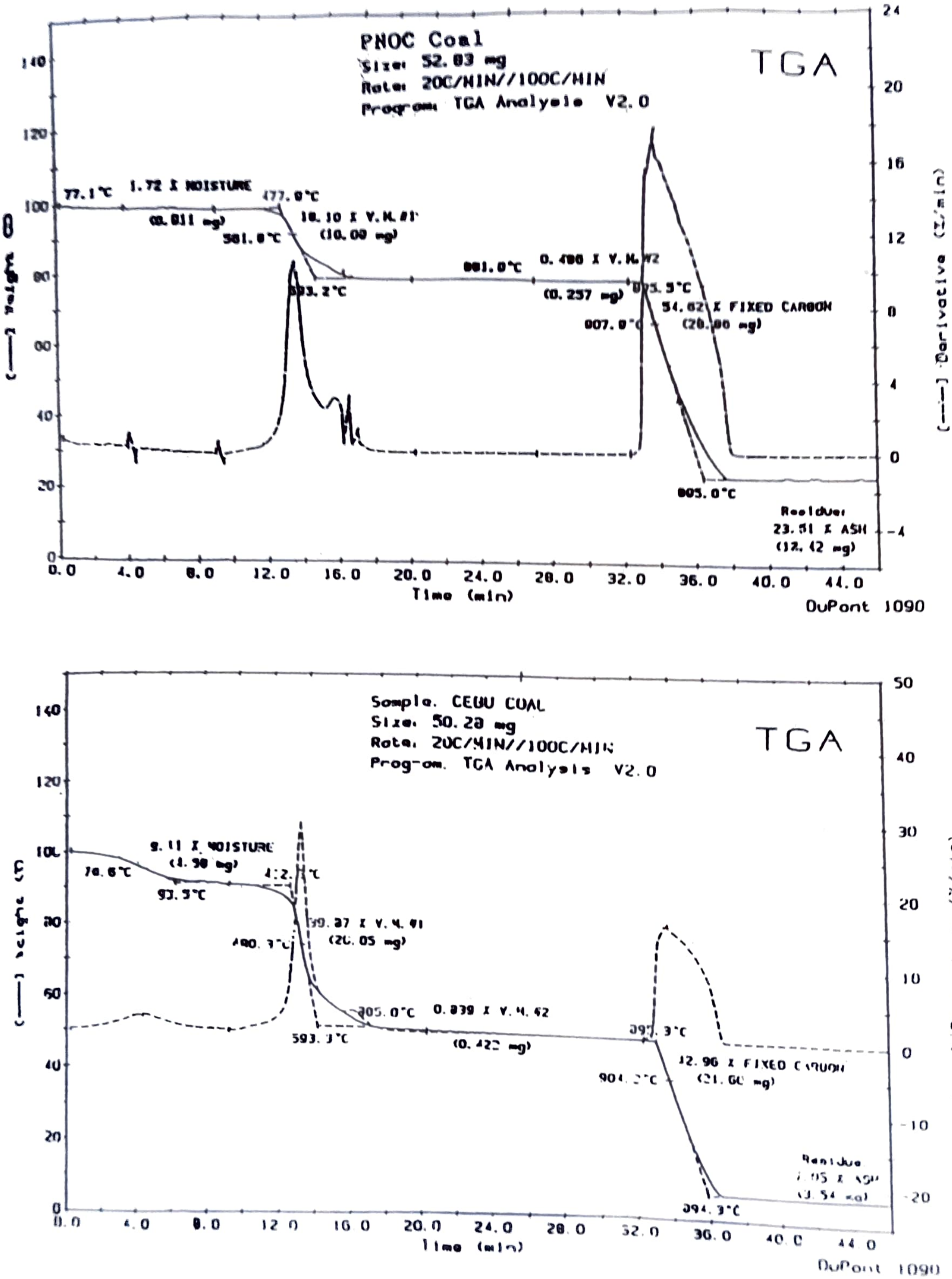


Figure 2
TGA Plots for PNOC and Cebu Coals

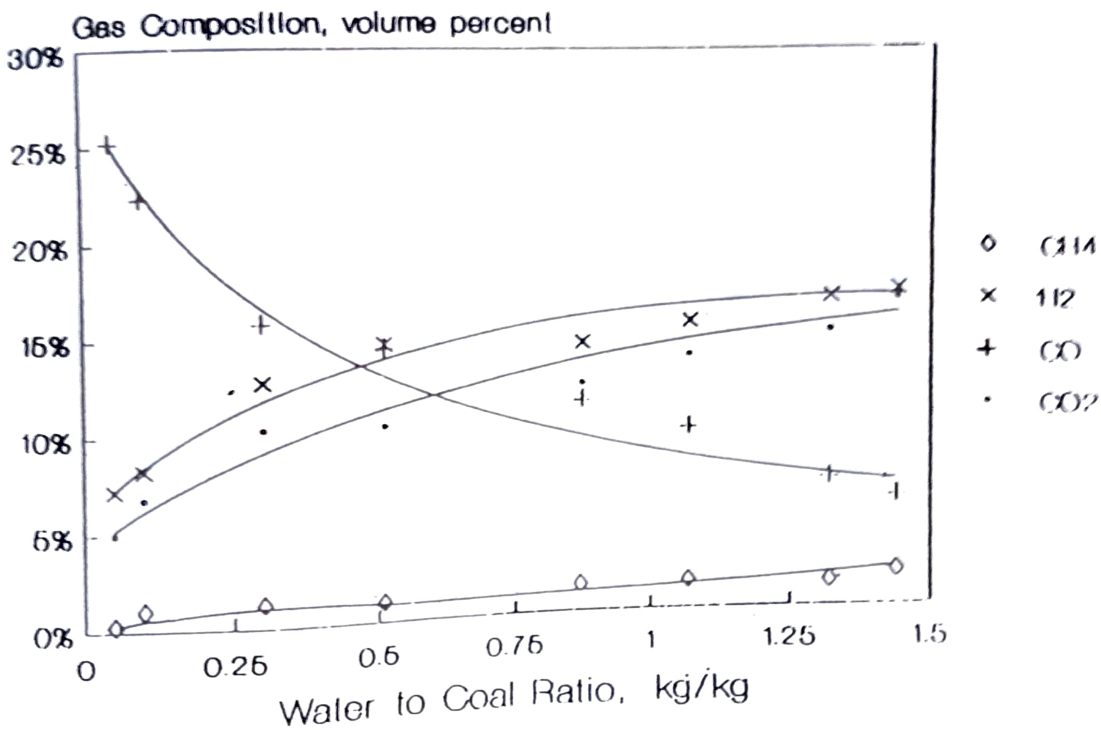


Figure 3
Effects of Water to Coal Ratio (*wcr*)
On Product Gas Composition of Cebu Coal
(Experimental Values)

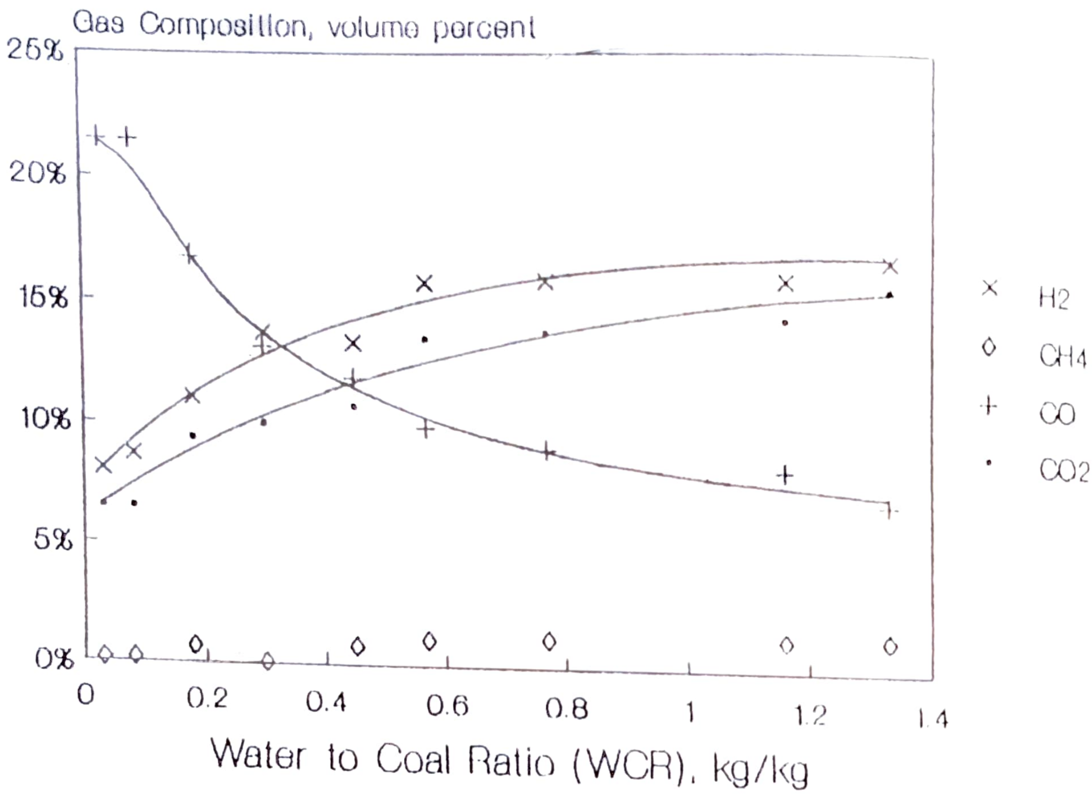


Figure 4
Effects of Water to Coal Ratio (*wcr*)
On Product Gas Composition of PNOC Coal
(Experimental Values)

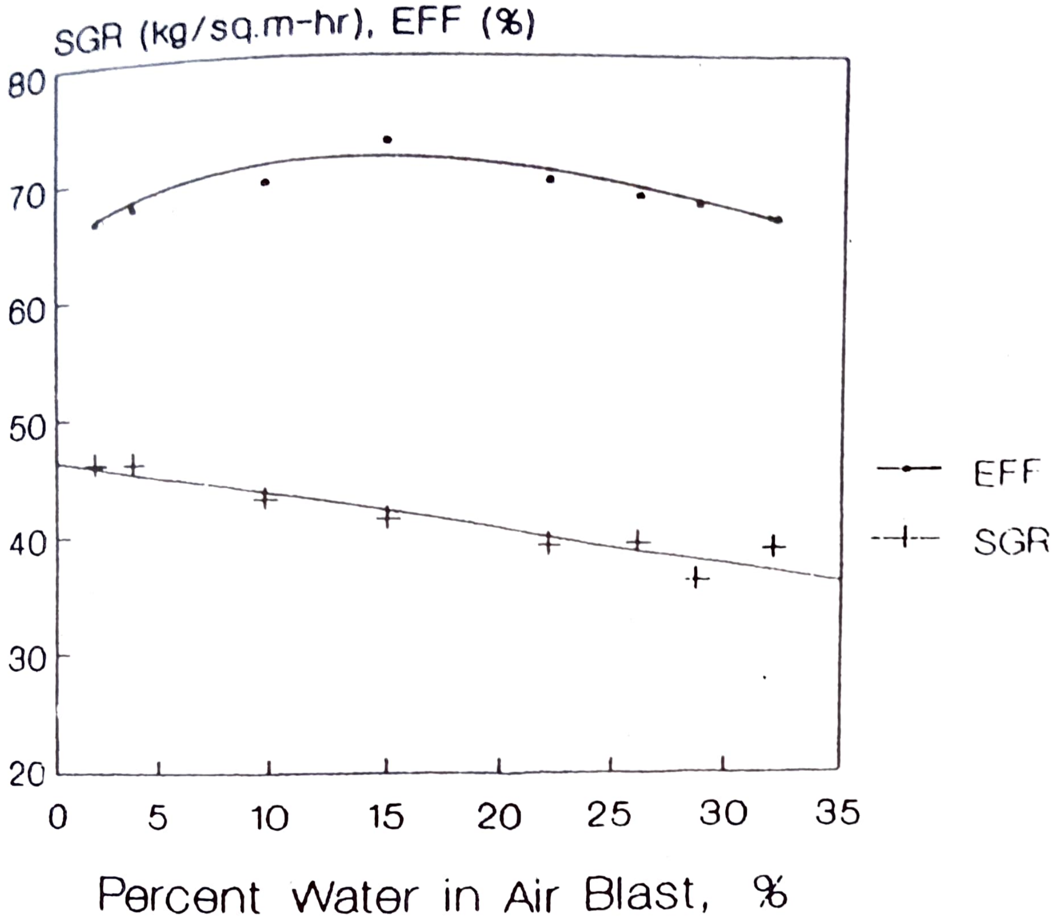


Figure 5
Effects of Water on Specific Gasification Rate (*SGR*) and Gasification Efficiency (*EFF*) for Cebu Coal

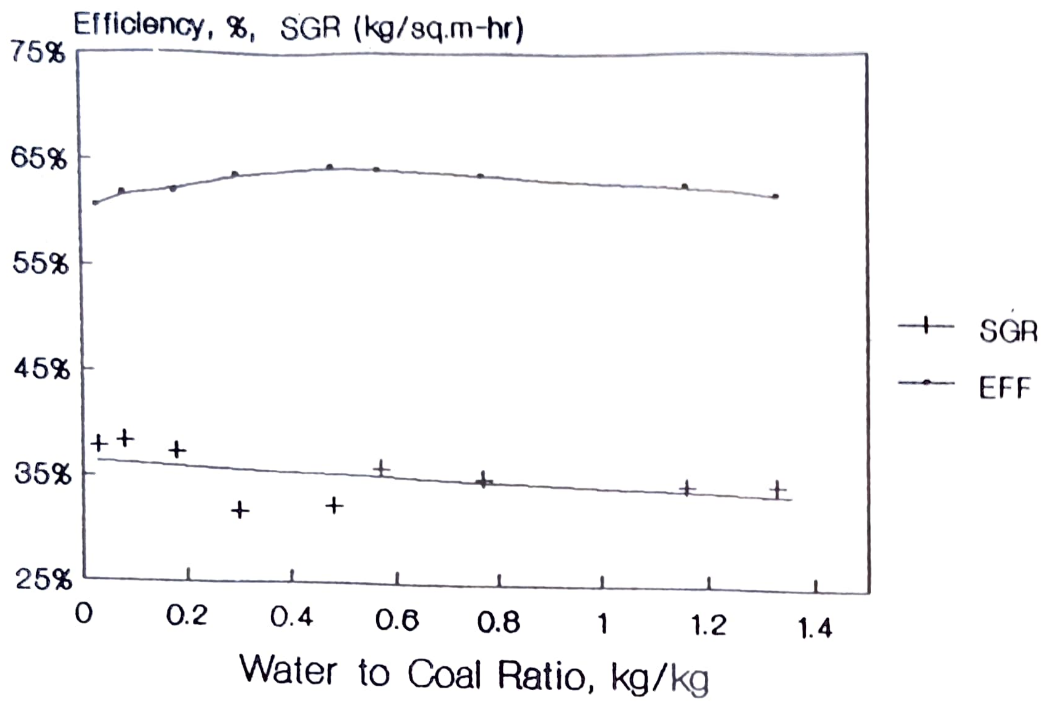


Figure 6
Water to Coal Ratio (*wcr*) vs. Efficiency (*EFF*) and Specific Gasification Rate (*SGR*) for PNOC Coal

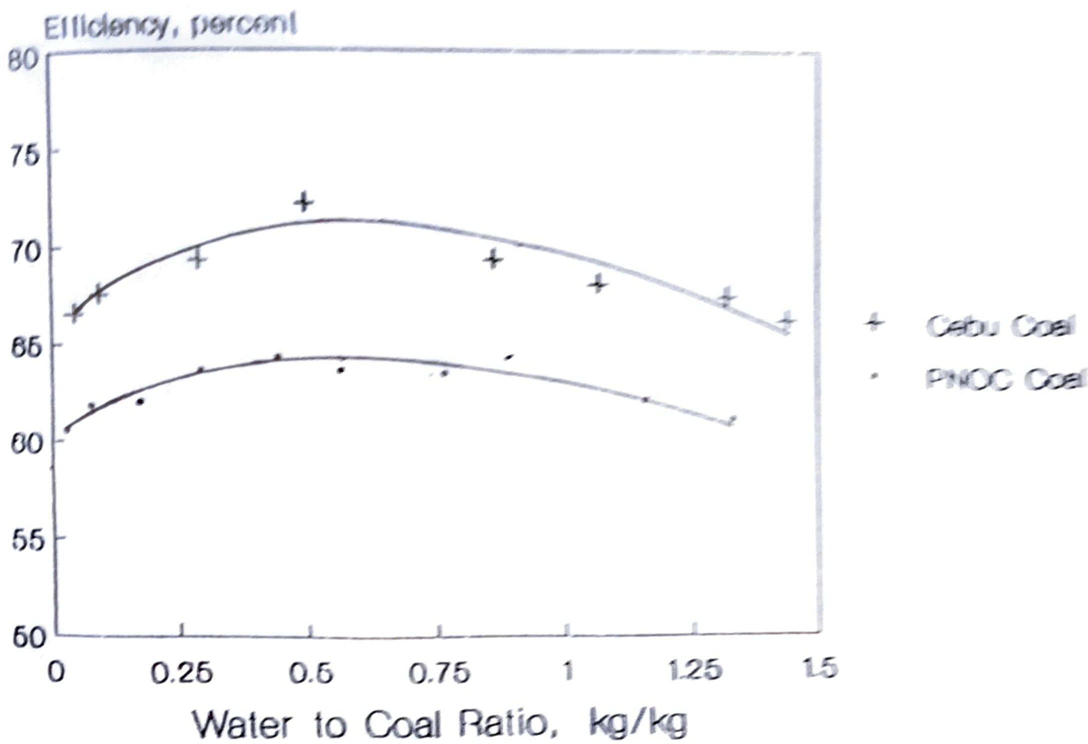


Figure 7
Water to Coal Ratio (*wcr*) vs. Gasifier Performance for Local Coals (Experimental Values)

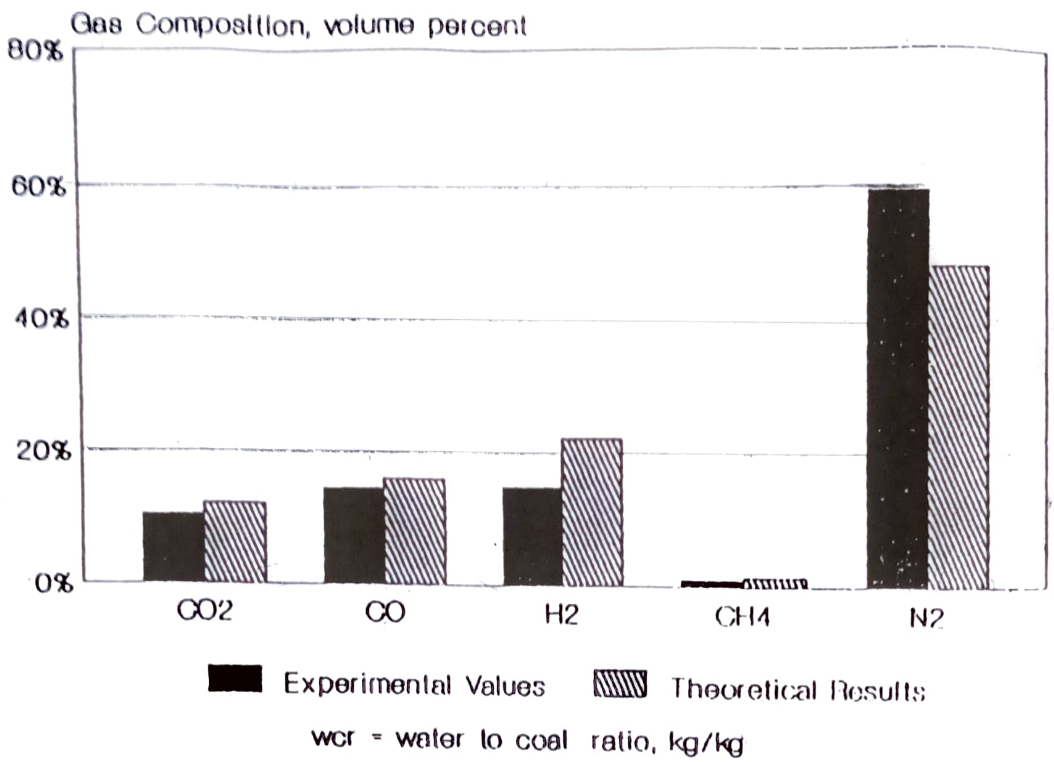


Figure 8
Comparison of the Mathematical and Experimental Product Gas Composition for Cebu Coal (*wcr* = 0.53)

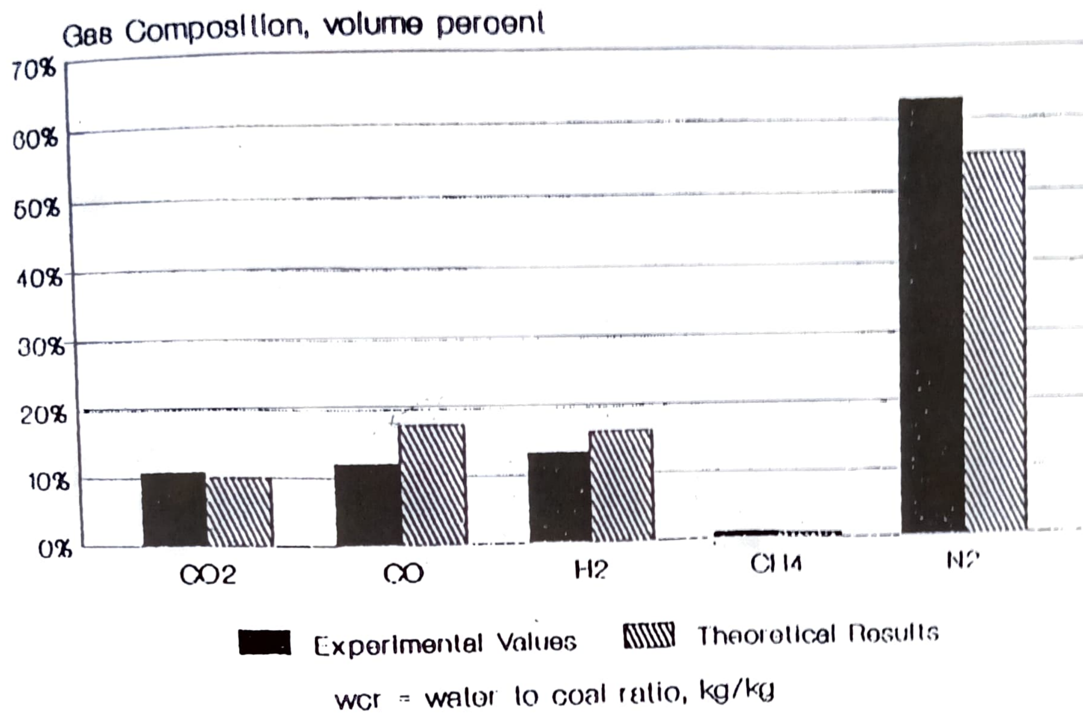


Figure 9
Comparison of the Mathematical and Experimental Product Gas Composition for PNOC Coal (*wcr* = 0.48)

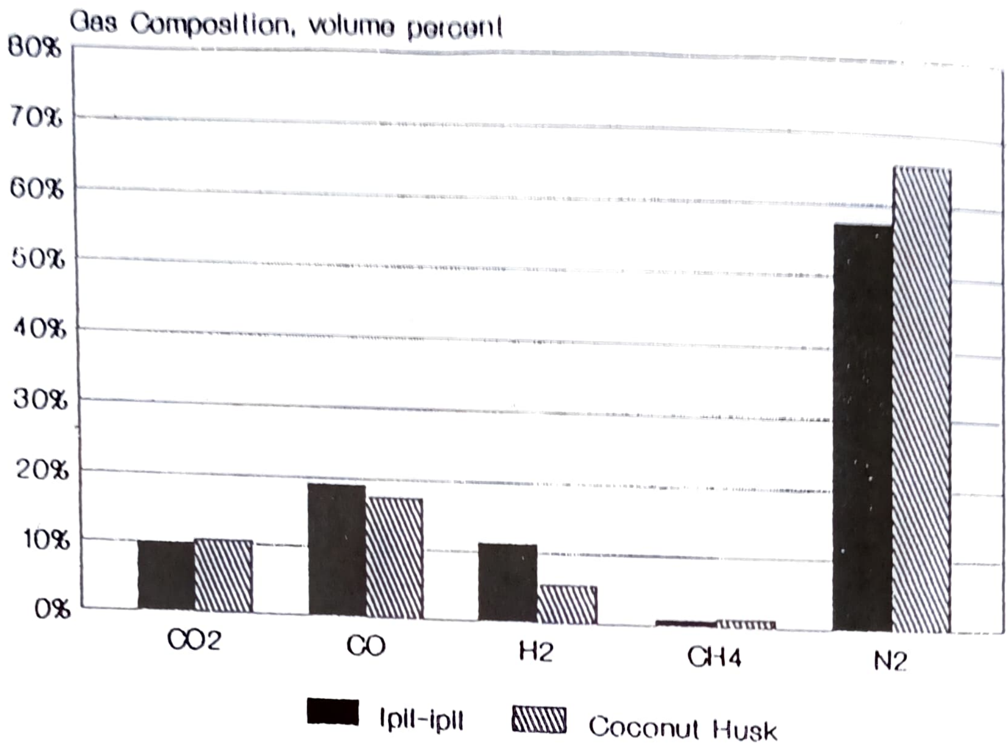


Figure 10
Comparison of the Product Gas Compositions of Coconut Husks and Ipil-ipil Wood Chips (Experimental)

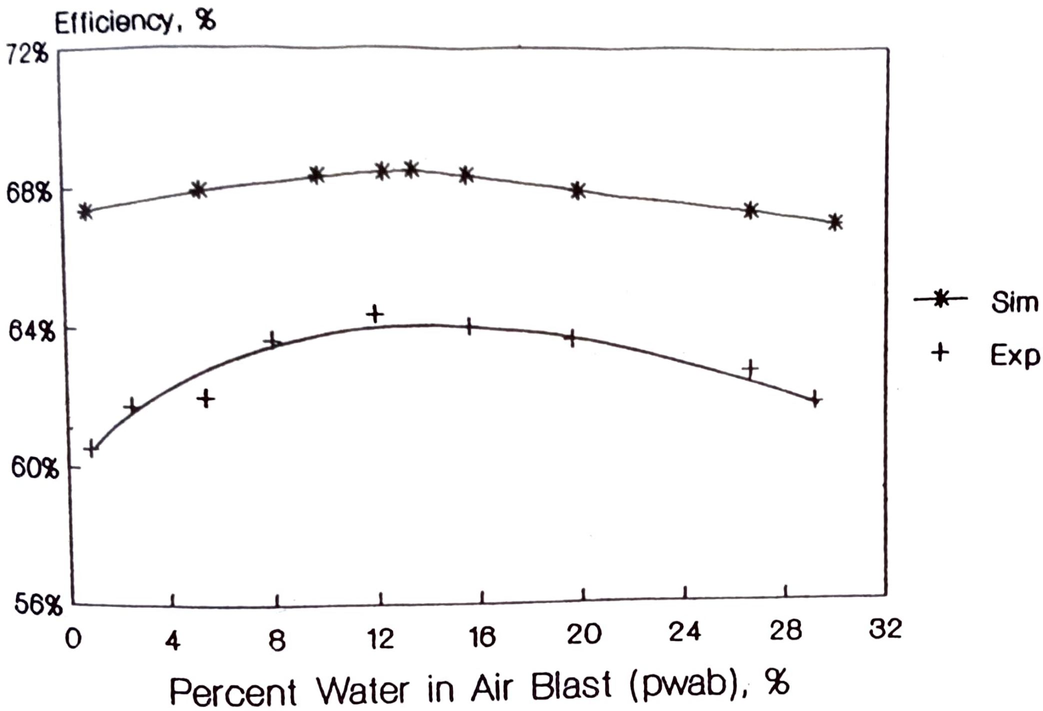
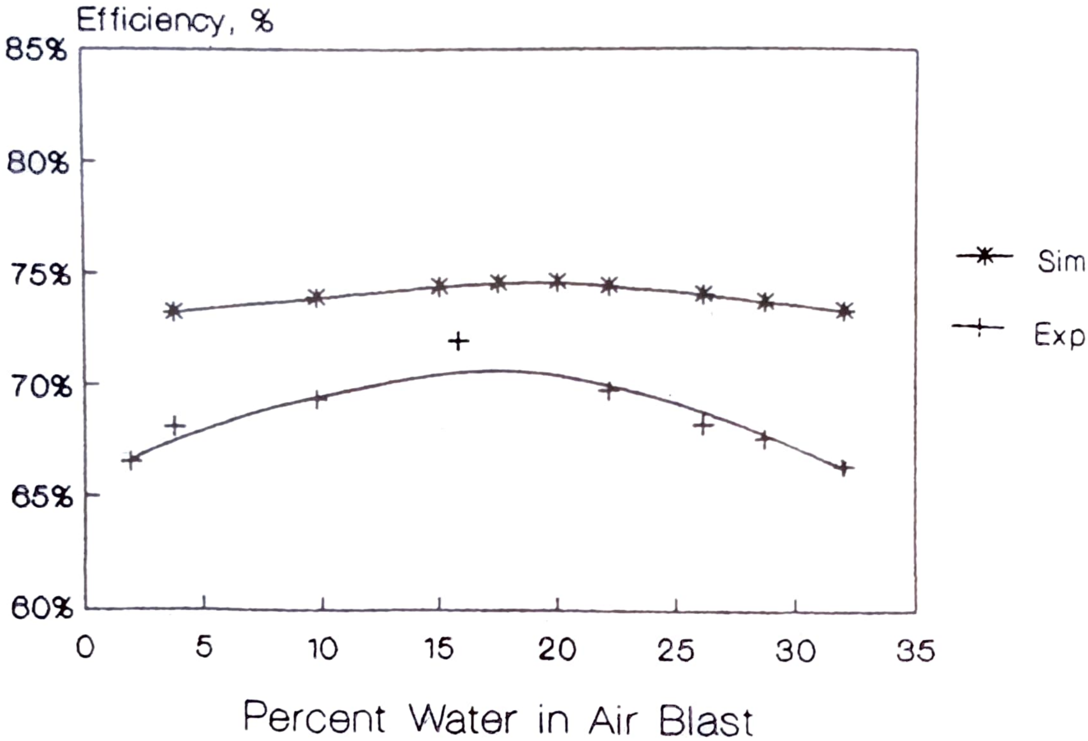


Figure 11
Effects of Water on Gasifier Performance for PNOC Coal (Experimental and Simulation Results)



Exp - experimental values
Sim - simulation results

Figure 12
Effects of Water on Gasifier Performance for Cebu Coal (Experimental and Simulation Results)

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