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# A COMPUTATIONAL MODEL FOR GASIFICATION OF BIOMASS WASTE IN VIETNAM

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## Abstract

Biomass is seen as an important part of a future, renewable energy mix, because unlike wind or solar energy, biomass based power generation can be operated on demand and can provide both heat and power. In this paper, a thermochemical model is used to predict the performance of a gasifier. Different biomass materials agricultural byproduct are tested using the model and forest residual is shown to be the most energetic one. For this material, the gasification temperature, syngas composition and calorific value are calculated. The effects of moisture content, air/fuel ratio, air inlet temperature are also investigated. The air inlet temperature is found to be the only way to increase the gas calorific value and cold gas efficiency. The air/fuel ratio, on the other hand, plays a rule key in controlling the gasification temperature and CO, $H_2$ and $CH_4$ ratio.

## 1. Introduction

Biomass as a new source of energy has drawn worldwide attention during the last decade. Positive rate of consumption of fossil fuels, negative rate of their natural reservoirs and restricting environmental rules have created awareness for the need to identify alternative sources of fuel such as biomass. Byproducts of activities like agriculture, food processing or wood industry are categorized as biomass materials. These materials were used to dispose in open lands creating serious environmental problems. Composting, recycling and incineration have been used as alternative methods for waste handling [1]. More recently, gasification of biomass materials has been introduced as another kind of waste to energy (WTE) conversion; a process to convert carbonaceous materials to synthetic gases such as $CH_4$, CO, $CO_2$ and $H_2$. One of attractive features of this technology include the ability to produce a clean syngas product that can be used either for generating electricity or producing chemicals.

It must be understood that gasification is *not* combustion. A combustion process needs stoichiometric feed of air/oxygen, while gasification process is performed at sub-stoichiometric conditions (30% to 70% of stoichiometric air/oxygen). In some cases, nitrogen and/or steam are also injected in order to control the gasification condition and volume of products. The many advantages of gasification over combustion make it feasible to review the possibilities of syngas production as a sink for biomass materials while observing the environmental regulations. In this technology, solid feed materials are gasified in a reactor such that virtually all of their contents are converted into fuel gas with calorific values typically 3±6 MJ/$m^3$ with most of the energy being available from $H_2$ and CO. After cleaning, this gas can be used to run small reciprocating engines, boilers, process heaters etc.

Biomass gasification is a complex process with many important controlling parameters such as air/fuel ratio and moisture content. As a result, mathematical models have been introduced for predicting the performance of gasifiers and as tools for their design optimization [2, 4]. One of these model, the equilibrium modeling, was used by many researchers. Although, thermodynamic equilibrium in reality never takes place in a gasification process [2], several works were performed to demonstrate the applicability of the equilibrium model for this process. Some equilibrium models were based on the minimization of Gibbs free energy [5] while others were based on equilibrium constant. The influence of important parameters of a gasification process such as: the air/fuel ratio, biomass moisture content, etc. These characteristics are the syngas composition, gasification temperature, calorific value of the producer gas and the cold gas efficiency.

## 2. Potential biomass waste in Vietnam

### Agricultural residue

Agricultural residue is the most important source of biomass in Vietnam. It accrues either as crop residue directly in the fields or afterwards during the processing of agricultural products. The crop residue ratio (CRR) indicates the proportion of residue within a certain quantity of crop and can be used to estimate the amount of residue remaining. However, note that the CRR can only be used to calculate the *theoretical* biomass potential.

Following production increases in recent years, nearly 44 million tones rice was produced in this country in 2012 [9]. Rice production also results in huge amounts of rice straw and rice husk. Rice straw often remains on farms as animal feed or is burned directly on the fields or dug into the soil. The rice husk accruing during the processing of rice grains is partly used as fuel for cooking stoves, as fertilizer, or as aggregate in cement and brick production. In recent years, it has also been compressed into briquettes and sold as fuel. The figures for the amount of rice straw available vary between 17 and 50 million t/a rice straw and from 2 to 8 million t/a of rice husk [3,9].

Sugarcane is another important agricultural product. During the harvest, about 40% of the crop (tips and leaves) accumulates as residue and is mostly left unused in the fields. During sugar production, another 15–35% of the crop is left as bagasse. Bagasse is mainly incinerated to generate energy in the sugar industry, although smaller quantities are used as animal feed.

Due to the increased demand for animal feed, maize cultivation has more than doubled in the past decade. The residue comprising the stems and empty corn cobs is sometimes used as animal feed or cooking fuel. About one million t/a empty corn cobs and another 9 million t/a of stems are assumed to accrue.

After rice, coffee is Vietnam's second-most important agricultural export. In 2012, coffee production reached approximately 1.1 million tones. The residue comprised 130,000–170,000 tones coffee pods.

Cassava production has developed very dynamically in recent years. Mainly processed into starch, the annual harvest is almost 10 million tones. Production involves solid residue in the order of 2.5–3 million t/a cassava stems.

Table 1- Overview of production and residue quantities of Vietnam's main crops (2014) in (Mio.t) [9]

| | |
|---|---|
| Rice straw | 17.0–50.0 |
| Rice husk | 2.0–8.0 |
| Leaves, top of Sugarcane | 7.6 |
| Bagasse | 2.4–7.8 |

| | |
|---|---|
| Maize cobs | 1.0 |
| Maize stalks | 9.0 |
| Coffee bean shells | 0.1–0.2 |
| Cassava stems | 2.5–3.0 |
| Peanut shells | 0.2 |
| **Total** | **41.8 – 86.8** |

### Wood residue

Vietnam has about 13 million hectares of forestland: 10 million hectares of natural forest and 3 million hectares of plantations. To determine the theoretical yield of wood in natural forests and forest plantations, the following sustainable impact rates are assumed [7]:
Natural forest: 1.0 t/ha/a,
Forest plantation: 2.5 t/ha/a.

This results in an annual wood yield of approximately 17.5 million tones. In 2010, about 5 million m³ of domestic wood was processed in the wood-processing industry, 90% of which came from plantations. Even so, the majority of the total wood used (> 70%) is imported. During processing, waste accrues in the form of wood chips, bark and sawdust. The following table summarizes the theoretical total amounts of wood and wood waste.

*Table 2 - Energy potential biomass agricultural byproduct in Vietnam*

| Potential Material: (Mio.t) | Energy Equivalent (Mio. Toe) | Quote (%) |
|---|---|---|
| Rice husk: 32.52 | 7.30 | 60.4 |
| Bagasse: 6.50 | 2.16 | 17.9 |
| Other: 9.00 | 1.80 | 14.9 |
| Total: 53.43 | 12.08 | 100.0 |

Table 3 - Amounts of wood and wood waste (in million t/a) [9]

| | |
|---|---|
| Natural forest | 6.8–10.3 |
| Forest plantation | 3.8–9.7 |
| Scattered trees | 0.5–7.8 |
| Wood processing industry | 4.0–6.7 |
| Waste wood | 0.8 |
| **Total** | **15.1–35.3** |

### Organic municipal solid waste

In recent years, Vietnam's growing economic strength and prosperity have led to sharp increases in the amount of refuse generated – not just industrial but also municipal waste. Not surprisingly, the conurbations are responsible for the highest increases in the quantities of waste. The specific amounts are between 0.7 and 1.3 kg/head/day [9], about 70–80% of which is collected and sorted. In the agricultural areas, both the specific amount of waste and the collection and sorting rate are much lower, probably in the order of 20–45%. Depending on the settlement structure and season, the levels of organic components in solid municipal waste vary substantially between 55 and 90%.

### Current status and problems of utilization of crop residues

The comprehensive utilization rate of crop residue is rather low, a large number of them was unreasonably used. At present, crop residues is mainly used as fuel, feedstuff, fertilizer and industrial raw material. With improved living conditions in rural areas, farmers tend to rely more on commercial fuel, which leads to even more open field burning of them, and brings water pollution, air pollution, global warming, negative effects to human health and potential energy waste as well. In other hand, it is easily causing fires, traffic accidents, effecting the road traffic safety.
Several scenarios will be examined on the basis of the available technological options

and the amount of unused crop residue to identify solutions for sustainable biomass use in Vietnam. In this study, we define "sustainable biomass use" as a method, which uses available biomass sources optimizing the material use, energy flow, and economic benefits, while the effects on soil quality and the environment are of an acceptable degree.

Potential biomass energy are presented in quantities and where possible, the distribution within the country is also provided in following diagram.

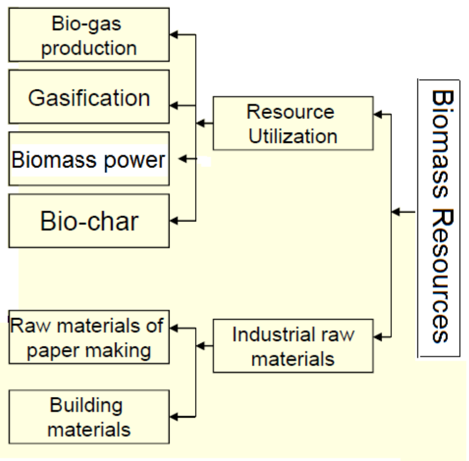

Fig. 1 – Way of utilization of biomass resource

### Biomass Gasification

Biomass Gasification is a thermochemical process that converts biomass into useful convenient gaseous fuels or chemical feedstock. It has emerged as a promising technology to fulfill the increasing energy demands of the world as well as to reduce significantly the volume of biomass waste generated in developing societies.

This process is also an important energy source in Vietnam, especially in rural areas. It is estimated that about 70% of rural population in Vietnam are currently relied on biomass as a daily cooking fuel. Biomass is also used to produce thermal energy in various small industries and handicraft facilities such as the traditional brick-kilns, lime-kilns, pottery-kilns, small sugar refineries, household-scale bakeries, etc.

In 2005, the total biomass used for thermal energy production was $13,513.10^3$ toe, of which $8,750.10^3$ toe (24.4 million tons) was from fuel wood, $1,895.10^3$ toe (7.8 million tons) from paddy straw, $915.10^3$ toe (3.0 million tons) from rice husk, $265.10^3$ toe (1.5 million tons) from bagasse, and $1,688.10^3$ toe (8.5 million tons) from other biomass types. Fuel wood accounted for 64.8% of total biomass consumption (in energy unit), paddy straw 14.0%, rice husk 6.8%, bagasse 2.0%, and other biomass 12.4%.

## 3. Thermodynamic calculating Equilibrium Models

### Composition of Biomass

Every biomass type has carbon, hydrogen, and oxygen as major chemical constitutive elements. These element fractions can be quantified with the ultimate analysis. Ultimate analyses are reported using the CxHyOz formula where x, y, and z represents the elemental fractions of C, H, and O, respectively. To fully describe biomass characteristics, it is customary to provide the proximate analysis. Under table is ultimate compositions of a diverse variety of biomass in Vietnam.

Table 4 – Ultimate analyses of a diverse variety of biomass compositions in Vietnam (wt. %) [3]

| Component | C | H | O | N | A | W |
|---|---|---|---|---|---|---|
| Rice husk | 39.79 | 5,23 | 38.63 | 0.13 | 13.92 | 2.30 |
| Rice straw | 39.20 | 5.10 | 38.50 | 0.6 | 18.50 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Coconut husk | 46.22 | 5.20 | 41.63 | 0.26 | 3.00 | 3.69 |
| Cassava stems | 44.34 | 5,76 | 42.37 | 0.65 | 4.50 | 2.38 |
| Bagasse | 45.39 | 6.16 | 33.59 | 0.16 | 1.29 | 13.40 |
| Coffee shell | 44.80 | 6.20 | 36.00 | 0.96 | 3.10 | 8.87 |
| Peanut shell | 48.62 | 5.96 | 36.69 | 0.93 | 2.7 | 5.10 |
| Saw dust | 47.10 | 6.50 | 45.4 | 0 | 1.00 | |

Biomass contains a large number of complex organic compounds, moisture (W), and a small amount of inorganic impurities known as ash (A). A typical ultimate analysis is:

$C + H + O + S + A + W = 100\%$.

The use of an equilibrium model assumes that the residence time of the reactants in the gasifier is high enough to reach chemical. The main product gases CO, $CO_2$, $H_2O$, $H_2$, $CH_4$ and char are at equilibrium. Nitrogen is considered inert.

All gases are assumed to behave as ideal gases.

Chemical equilibrium is determined by either of the following:

- The equilibrium constant and
- Minimization of the Gibbs free energy.

In a gasifier the air supply is only a fraction of the stoichiometric rate. The term equivalence ratio (ER) is often used in connection with gasifier air supply. Equivalence ratio is defined as the ratio of actual air fuel $L_0$ ratio to the stoichiometric air fuel ratio L.

An excessively low value of (ER) (0.2) results in several problems including incomplete gasification, excessive char formation and low heating value of the product gas. On the other hand, too high a value of (ER) (0.4) results in excessive formation of products of complete combustion, such as $CO_2$ and $H_2O$ at the expense of desirable products like CO and $H_2$. This causes a decrease in the heating value of the gas. In practical gasification systems, the value of (ER) is normally maintained at 0.20 to 0.30 [4].

The dry air contains 21 % oxygen, 79 % nitrogen, by volume, the dry air required for complete combustion of a unit mass Lo, is given by:

$$L_0 = (1 + 3.76)(0.01867C + 0.056H - 0.007O)$$

Gasification yields combustible gases such as hydrogen, carbon monoxide, methane and char through a series of reactions. The following are for major gasification reactions:

1. Water–gas reaction: $C + H_2O = H_2 + CO - 131.38$ kJ/(mole carbon) .
2. Boudouard reaction: $CO_2 + C = 2CO - 172.58$ kJ/(mole carbon)
3. Methanation: $C + 2H_2 = CH_4 + 74.90$ kJ/(mole carbon)

The composition of the gas obtained from a gasifier depends on a number of parameters such as: fuel composition, gasifying medium, operating pressure, temperature, moisture content of the fuels, mode of bringing the reactants into contact inside the gasifier, etc. The product gas of gasification is generally a mixture of several gases, including moisture or steam. Given sufficient time the concentration of these gases will reach their equilibrium concentrations expressed in respective partial pressures:

$p_i = p(V_i/Vg)$, p is pressure of the reactor

$V_i$ is partial volume of gas, $V_g = V_{H2} + V_{H2O} + V_{CO} + V_{CO2} + V_{CH4} + V_{N2}$ $(m^3/kg)$

In the stoichiometric method, the model incorporates the chemical reactions and species involved. It usually starts by selecting all species containing C, H, and O, or any other dominant elements. If other elements form a minor part of the product gas, they are often neglected.

When $L_0$ is actual air fuel denote the air supply and L is air supply for stoichiometric conditions in ($m^3$ dry air)/(kg dry fuel), then $L_0 = (ER)L$ and C is the carbon content of the fuel, (kg carbon)/(kg dry fuel). For Carbon is split between CO, $CO_2$, $CH_4$ and char, we have Carbon balance:

$$1.867C^p = V_{CO2} + V_{CO} + V_{CH4} + 1{,}867C^* \quad (1)$$

C* is (kg char)/(kg dry fuel)

With W represents the moisture content of fuel, (kg water)/(kg dry fuel), the Hydrogen balance is:

$$12.2H + 1.244W + 0.001244G_{H2O}(ER)L_0 = V_{H2} + V_{H2O} + 2\,V_{CH4} \quad (2)$$

H - Hydrogen content of the fuel (kg hydrogen)/(kg dry fuel)
$G_{H2O}$ - humidity associated with air, g/($m^3$ dry air)

If O is the oxygen content of the fuel (kg oxygen)/(kg dry fuel), then we write the molar balance of $O_2$ as follows:

$$0.7O + 0.623W + (ER)L_0(0.21 + 0{,}001244g_{H2O}16/18) = 0.5(V_{CO} + V_{H2}) + V_{CO}. \quad (3)$$

N is the nitrogen content of the fuel (kg nitrogen)/(kg dry fuel), the molar balance of $N_2$ gives:

$$0.8N + 0.79(ER)L_0 = V_{N2} \quad (4)$$

For a gasifier pressure p, the equilibrium constants k for reactions:

$k_1 = p^2_{CO}/p_{CO2}$ Water–gas reaction (5)

$k_2 = p_{CO}.p_{H2}/p_{H2O}$ Boudouard reaction (6)

$k_3 = p_{CH4}/p^2_{H2}$ Methanation (7)

To estimate the values of the seven unknowns:
$V_{H2}$, $V_{H2O}$, $V_{CO}$, $V_{CO2}$ ,$V_{CH4}$,$V_{N2}$ and C*
We need a total of seven equations from (1) to (7).

An energy balance, based on the 1 kg dry fuel, for the process can be described by the following equation:

$$LHV_B + c_A(ER)L_0T_A = V_gLHV_g + Vc_gT_g + Q \quad (8)$$

Where: $c_A$ is specific head capacity of air, J/($m^3$K);

$c_g$ is specific head capacity of product gas, J/($m^3$K);

$LHV_B$ - biomass low heating value in kJ/kg;

$T_a$ - temperature of gasification air, °C;

$T_g$ - temperature of produced gas, °C;

On the left hand side of the equation, the two terms describes the total heat of formation and the enthalpy for air stream. The two first terms on the right hand side describes the total heat of formation and the total enthalpy for all product species. The heat loss of the system to the surroundings is denoted by Q.

$$LHV_B = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1A - 22.6(9H + W) \text{ kJ/kg} \quad (9)$$

Produced gas low heating value in kJ/$m^3$(N):

$$LHV_g = 12.63V_{co} + 35.80V_{CH4} + 10.79V_{H2} \quad (10)$$

For established biomass ultimate analysis, temperature of gasification air and temperature of produced gas, combining the mass balance equations (1), (2), (3) and (4) with the equations for the equilibrium constants, (5), (6), (7), and equation of energy balance (8), the equivalence ratio (ER) and composition of produced gas can be obtained.

The model of the gasification has been studied with different parameter values to evaluate its performance. This has been done by using a calculating Program. Two parameters have been studied: $T_a$ - temperature of gasification air and Tg - temperature of produced gas to equivalence ratio (ER) and composition of produced gas.
The composition for the fuel used in the study is from bagasse, (component value in % mass) with component in table 4.

Following diagrams present influent of produced gas temperature on their gas low heating value $LHV_g$ and composition of produced gas CO, $H_2$, $CH_4$ with the different of supply air temperature $T_a$.

The following diagrams represent influents of the produced gas $T_g$ on the low heat value of the gas (LHVg), the quote of carbon oxide CO, the volume percent of hydrogen H and the quote of methane $CH_4$ with different temperature of gasification air $T_a$.

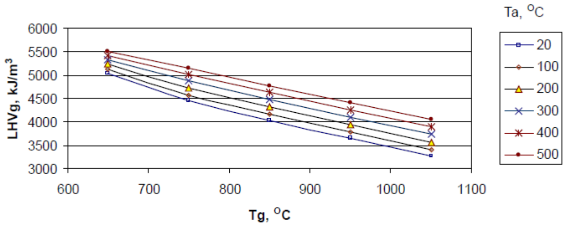

Fig. 2 – Influence of the temperature of the produced gas on the low heat value of the gas (LHVg) with different temperature of gasification air.

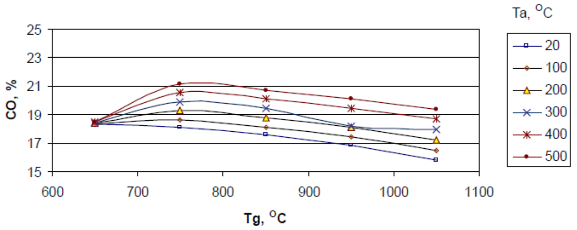

Fig. 3 – Influence of the temperature of the produced gas on the quote of carbon oxide CO with different temperature of supply air.

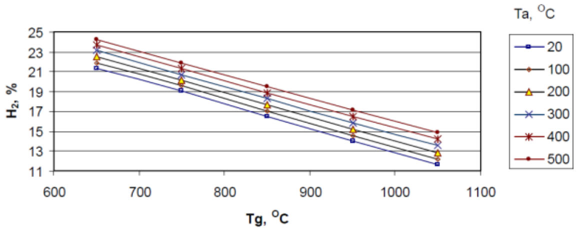

Fig. 4 – Influence of the temperature of the produced gas on the volume percent of hydrogen with different temperature of gasification air.

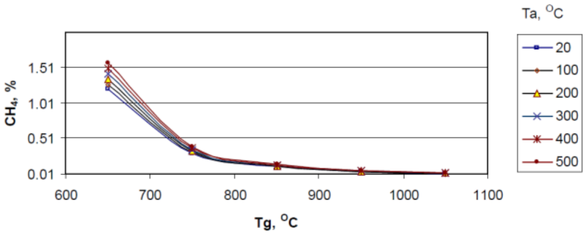

Fig. 5 – Influence of the temperature of the produced gas on the quote of methane $CH_4$ with different temperature of gasification air.

A computing model was developed for a biomass gasifier in order to calculate the composition of the producer gas and investigate the gasification characteristics. The model was then employed to evaluate the capability of different biomass materials to produce energy. The effects of moisture content, air inlet temperature, air/fuel ratio on gasification characteristics were investigated. Although, the increase of air inlet temperature was the only way to increase the producer gas calorific value and cold gas efficiency, it also increased the gasification temperature which was not favorable.

The developed model in this study can be used to simulate gasification of other types of biomass materials and predict the effect of important variables in optimization of a biomass gasifier.

The model of the gasification has been studied with different parameter values to evaluate its performance. It can be used for estimation and design of gasification equipment.

## 4. Conclusion

A mathematical thermodynamic equilibrium model was developed for a biomass gasifier in order to calculate the composition of the producer gas and investigate the gasification characteristics. The model was then employed to evaluate the capability of different biomass materials to produce energy. Thus the model can be used as a predictive simulation tool for industrial gasifier.

## Nomenclature

c – Specific head capacity,
ER – Equivalence ratio,
LHV – biomass low heating value,
T – Temperature,
V – Volume,

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