Gasifier System Identification for Biomass Power Plants Using Response Surface Method

J. SATONSAOWAPAK, T. RATNIYOMCHAI, T. KULWORAWANICHPONG, P. PAO-LA-OR., B. MARUNGSRI., and A. OONSIVILAI
Alternative and Sustainable Energy Research Unit, School of Electrical Engineering
Institute of Engineering, Suranaree University of Technology
111 University Avenue, Muang District, Nakhon Ratchasima, 30000
THAILAND
*Corresponding author: anant@sut.ac.th

Abstract: - Biomass in the form of wood has been used by human as a source of energy for a long period of time. Recently, the use of renewable energy sources has been widely experienced in domestic, commercial, and industrial appliances. This has resulted in a greater awareness and advancement in renewable energy technology. Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion. Many gasifier models have various operating conditions and the parameters kept in each model are also different. In this paper, the experimental data applied have three inputs; which are biomass consumption, air flow rate and ash discharge rate. The model presents gas flow rate as an output. The response surface model, multiple linear regression, quadratic model as well as cubic model were used to identify the Gasifier system and results are presented.

Key-Words: - Gasifier System, Identification, Response Surface Method, Biomass, Modelling

1 Introduction
The use of renewable and sustainable energy resources will play a major role in many aspects of electricity generation. In particular, due to environmental issues and ever increasing energy demands, the world is forced to look for alternative energy sources. Also, it is anticipated that shortage of hydrocarbon fuel will be inevitable. In terms of population growth, it has been estimated that by the year 2060, the world population will be in excess of 12 billions. Currently, over 80 percent of the crude oil reserves are under the control of only eight countries. Therefore, a number of strategies, such as special tariff and subsidy agreements, have been established in many countries in order to stimulate the research and utilization of alternative energy sources [1].

Biomass is the organic material, which has stored solar energy from sunlight in the form of chemical energy in the plants through the process called photosynthesis. Biomass fuels include agricultural wastes, crop residues, wood, woody wastes, etc. Unlike fossil fuels, biomass does not add carbon dioxide to the atmosphere as it absorbs the same amount of carbon while growing. It is the cheapest, eco-friendly, renewable source of energy [2].

Power generation from biomass has emerged as a very interesting complement to conventional sources of energy because of its contribution to the reduction of the green house effect [3]. Biomass is recognized to be one of the major potential sources for energy production. There has been an increasing interest for thermo-chemical conversion of biomass and urban wastes for upgrading the energy in terms of more easily handled fuels, namely gases, liquids, and charcoal in the past decade. It is a renewable source of energy and has many advantages from an ecological point of view [4]. Biomass fuels are characterized by high and variable moisture content, low ash content, low density, and fibrous structure [5]. Biomass gasification is a technology that transforms solid biomass into syngas (hydrogen and carbon monoxide mixtures produced from carbonaceous fuel). It is important and efficient energy conversion technology along with interventions to enhance the sustainable supply of biomass fuels can transform the energy supply situation in rural areas [4].

Gasifier system is an important part to produce fuel gas. This paper studied the experimental data which have three inputs that are biomass consumption, air flow rate and ash discharge rate and one output is gas flow rate. This is the energy conversion technologies which is suitable for small-scale.

The response surface method has been widely used in practical engineering design optimization problems [6]. This method originates from science
disciplines in which physical experiments are performed to explore the unknown relations between a set of variables and the system output, and these unknown relations are modeled as polynomials using the least square method. These straightforward polynomial models allow the objective and constraints of the optimization to be evaluated quickly to obtain better search points for more accurate surrogate models and eventually converge to the global optimum [7].

This paper is divided into five sections. Section 1 gives the introduction. Section 2 presents gasification system. Section 3 presents response surface method. Section 4 shows results. Finally, conclusions are presented in section 5.

2 Biomass Gasification
Biomass fuels are characterized by high and variable moisture content, low ash content, low density and fibrous structure. In comparison with other fuels, they are regarded as a low quality despite of low ash content and very low sulfur content [3]. Biomass gasification system consists of two main parts: the gasifier, and the gas cleaning system. In this paper, the downdraft gasifiers which are simple and robust are used. The gas exiting the reactor flowed through a cyclone and scrubbers just to remove a dust and the tars. Next, the clean gas passed through several heat exchangers to condense water vapor. After that, the gas is conditioned to be used in the internal combustion engine [3].

2.1 Gasifier
Biomass gasification converts solid biomass into more convenient gaseous form. This process is made possible in a device called gasifier. The following subsections provide the details of the gasifier process and chemical reaction.

2.1.1 Process zone
Four distinct process take place in a gasifier as the fuel makes its way to gasification. They are drying zone, pyrolysis zone, combustion zone, and reduction zone.

2.1.2 Chemical reaction
The following are major reactions that takes place in combustion and reduction zone [8].

1. Combustion zone:
The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen, usually as steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450 °C. The main reactions are:

\[ \text{C} + \text{O}_2 = \text{CO}_2 \quad (+393 \text{MJ/kg mole}) \quad (1) \]

\[ 2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O} \quad (-242 \text{MJ/kg mole}) \quad (2) \]

2. Reaction zone:
The products of partial combustion (water, carbon dioxide and uncombusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place.

\[ \text{C} + \text{CO}_2 = 2\text{CO} \quad (-164.9 \text{MJ/kg mole}) \quad (3) \]

\[ \text{C} + \text{H}_2\text{O} = \text{CO} + \text{H}_2 \quad (-122.6 \text{MJ/kg mole}) \quad (4) \]

\[ \text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2 \quad (+42 \text{MJ/kg mole}) \quad (5) \]

\[ \text{C} + 2\text{H}_2 = \text{CH}_4 \quad (+75 \text{MJ/kg mole}) \quad (6) \]

\[ \text{CO}_2 + \text{H}_2 = \text{CO} + \text{H}_2\text{O} \quad (-42.3 \text{MJ/kg mole}) \quad (7) \]

Reactions (3) and (4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the reduction zone are normally 800-1000 °C. Lower the reduction zone temperature (~700-800 °C), lower is the calorific value of gas.

3. Pyrolysis zone:
Up to the temperature of 200 °C only water is driven off. Between 200 to 280 °C carbon dioxide, acetic acid and water are given off. The real pyrolysis, which takes place between 280 to 500 °C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed. Between 500 to 700 °C the gas production is small and contains hydrogen. In downdraft gasifier the tar have to go through combustion and reduction zone and are partially broken down. Since majority of fuels like wood and biomass residue do have large quantities of tar, downdraft gasifier is preferred over others.

4. Drying zone:
The main process is of drying of wood. Wood entering the gasifier has moisture content 10-30%. Various experiments on different gasifiers in different conditions have shown that on an average the condensate formed is 6-10% of the weight of gasified wood. Some organic acids also come out during the drying process. These acids give rise to corrosion of gasifiers.

3 Response Surface Method
Response surface method is a statistical and mathematical method that gives an effective practical means for design optimization. When response \( y \), which should be taken into
consideration for design, is determined as a function of multiple design variables \( x_i \), the behavior in response surface method is expressed by the approximation as a polynomial
\[
y = f(x_1, x_2, \ldots, x_k) + \varepsilon
\]
where the form of the true response function \( y \) is unknown or very complicated, \( f(x_1, x_2, \ldots, x_k) \) is a known polynomial function of \( (x_1, x_2, \ldots, x_k) \), and \( \varepsilon \) is a term that represents random error. It is assumed to be normally distributed with mean zero and variance.

Because the form of \( y \) is unknown, it must be approximated by a known polynomials function \( f(x_1, x_2, \ldots, x_k) \). The more suitable approximation for \( y \), the accuracy is higher. In general, the first-order polynomials is [11],[12]
\[
y = b_0 + \sum_{i=1}^{k} b_i x_i + \varepsilon
\]
(9)
The first-order model is likely to be appropriate when the experimenter is interested in approximating the true response surface over a relatively small region of the input variable space in a location where there is little curvature in \( f \). For a quadratic response function with \( k \) variables by a regression model, it is expressed by (10)
\[
y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon
\]
(10)
And, a cubic response function with \( k \) variables by a regression model, it is expressed by (11)
\[
y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j \\
+ \sum_{i=1}^{k} \sum_{j=1}^{k} \sum_{l=1}^{k} b_{iij} x_i x_j x_l + \varepsilon
\]
(11)
For this paper, the response function with \( k = 3 \) variables, the first-order polynomials is
\[
y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + \varepsilon
\]
(12)the quadratic response function is
\[
y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 \\
+ b_{22} x_2^2 + b_{23} x_2 x_3 + b_{33} x_3^2 + \varepsilon
\]
(13)
the cubic response function is
\[
y = \text{quadratic model} + b_{111} x_1^3 + b_{112} x_1^2 x_2 + b_{113} x_1^2 x_3 + b_{122} x_1 x_2^2 + b_{133} x_1 x_3^2 + b_{223} x_2^2 x_3 \\
+ b_{233} x_2 x_3^2 + b_{333} x_3^3 + \varepsilon
\]
(14)
where
- \( x_i \) is the biomass consumption (kg/h)
- \( x_2 \) is the air flow rate (kg/h)
- \( x_3 \) is the ash discharge rate (kg/h)
- \( y \) is the gas flow rate (kg/h)

Then, \( n \) sets of observation data in correspondence with design variables can be expressed by matrix representation in (15) and (16)
\[
\begin{align*}
\begin{bmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{bmatrix}
&= 
\begin{bmatrix}
1 & x_{11} & x_{12} & \cdots & x_{1k} \\
1 & x_{21} & x_{22} & \cdots & x_{2k} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & x_{n1} & x_{n2} & \cdots & x_{nk}
\end{bmatrix}
\begin{bmatrix}
b_0 \\
b_1 \\
\vdots \\
b_n
\end{bmatrix}
+ 
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\vdots \\
\varepsilon_n
\end{bmatrix}
\end{align*}
\]
(15)
\[
y = Xb + \varepsilon
\]
(16)
Coefficient vector \( b \) is obtained by the following equation using the condition where the square of error is minimized:
\[
b = \left( X^T X \right)^{-1} X^T Y
\]
(17)
where \( X \) the design matrix of sample data points is, \( X^T \) is its transpose, \( Y \) is a column vector containing the values of the response at each sample point.

By obtaining coefficient vector \( b \) from (17), the response surface is prepared [9].

### 4 Results and Discussion
The method described in the previous section was applied to estimate the coefficient of model. Fig.1-3 show values comparison of response surface method with observed data in different equation model. Fig. 1 presents comparison of linear equation with observed data. Fig.2 presents comparison of quadratic equation with observed data. Fig. 3 presents comparison of cubic equation with observed data. From these results, the error value can be calculated by using values from experiments compared with values from response surface method as shows in Fig. 4.

Table 1 shows the experimental data test for solving response surface method which was kept at biomass power plant in Suranaree University of
Technology. Table 2 presents the gas flow rate which approximated by using response surface method (linear equation, quadratic equation and cubic equation). Table 3 presents error values from different method. These errors were used to consider the response surface method which should be to be representd the gasifier system that had three outputs which were biomass consumption, ash discharge rate and air flow rate and one output is gas flow rate. From three equations, the cubic equation is most suitable than others equation for this experimental data. In the future, the method which better than three methods may be used to solve and present replace such as artificial intellligent (fuzzy, neuron network,etc.) which can used with complicated system and widely use in engineering fields[13-34].

![Fig. 1 comparison of linear equation with observed data](image1.png)

Fig. 1 comparison of linear equation with observed data

![Fig. 2 comparison of quadratic equation with observed data](image2.png)

Fig. 2 comparison of quadratic equation with observed data

![Fig. 3 comparison of cubic equation with observed data](image3.png)

Fig. 3 comparison of cubic equation with observed data

![Fig. 4 Gas flow rate error with linear equation](image4.png)

Fig. 4 Gas flow rate error with linear equation

Table 1: Experimental data test for solving response surface method

<table>
<thead>
<tr>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>103.90</td>
<td>13.00</td>
<td>117.2899</td>
<td>221.5537</td>
</tr>
<tr>
<td>138.30</td>
<td>15.20</td>
<td>117.7695</td>
<td>218.2254</td>
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<td>108.60</td>
<td>15.30</td>
<td>116.5175</td>
<td>225.4367</td>
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<td>119.40</td>
<td>13.80</td>
<td>116.2114</td>
<td>226.8789</td>
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<td>117.50</td>
<td>16.50</td>
<td>116.3934</td>
<td>225.9914</td>
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<tr>
<td>124.80</td>
<td>14.30</td>
<td>115.9330</td>
<td>227.9884</td>
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<tr>
<td>107.50</td>
<td>14.50</td>
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<td>138.10</td>
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<td>115.4149</td>
<td>230.2072</td>
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<td>114.00</td>
<td>16.20</td>
<td>114.7040</td>
<td>232.9808</td>
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<td>128.00</td>
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<td>233.2027</td>
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<tr>
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<td>119.50</td>
<td>14.60</td>
<td>116.3475</td>
<td>237.0857</td>
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<td>13.90</td>
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<tr>
<td>105.70</td>
<td>12.90</td>
<td>116.3644</td>
<td>239.6374</td>
</tr>
</tbody>
</table>
For this paper, the response function with the first-order polynomials from equation (12) is
\[
y = 679.1520 + 0.2486x_1 + 1.4018x_2 + 2.5493x_3
\]
(18)

the quadratic response function from equation (13) is
\[
y = (-60830) + (-6.4469)x_1 + (98.189)x_2 + (1049.6)x_3 + (0.019073)x_1x_2 + (0.051547)x_1x_3 + (-0.94989)x_2x_3 + (0.0018346)x_2^2 + (0.3572)x_3^2 + (-4.5033)x_3
\]
(19)

the cubic response function is from equation (14) is
\[
y = (8.2015e+006) + (-2796.2)x_1 + (-11704)x_2 + (-2.0779e+005)x_3 + (5.2532)x_1x_2 + (47.321)x_1x_3 + (200.53)x_2x_3 + (-0.025587)x_1^2 + (-11.763)x_2^2 + (1754.6)x_3^2 + (-0.035694)x_1x_2x_3 + (-0.032769)x_1^2x_2 + (0.0031139)x_1^2x_3 + (0.24306)x_1x_2^2 + (-0.20375)x_1x_3^2 + (0.22478)x_2^2x_3 + (-0.87786)x_2x_3^2 + (0.00035003)x_1^3 + (-1.0499)x_2^3 + (-4.9363)x_3^3
\]

5 Conclusion
Gasifier system is an important part to produce fuel gas. It is the good way to know the function which can use to predict the results. This study applied the experimental data which have three inputs that entry the system are biomass consumption, ash discharge rate and air flow rate and the output of system is gas flow rate which means fuel gas that used in the internal combustion engine. In the results, cubic equation is better than linear and quadratic equation.

6 Acknowledgement
The experimental data was supported by Center of Excellence in Biomass Suranaree University of Technology. The funds provided by SUT Research and Development Fund for this study.

References:


