Innovative Instrumentation and Analysis of the Temperature Measurement for High Temperature Gasification

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ABSTRACT

The systematic tests of the gasifier simulator on the clean thermocouple were completed in this reporting period. Within the systematic tests on the clean thermocouple, five (5) factors were considered as the experimental parameters including air flow rate, water flow rate, fine dust particle amount, ammonia addition and high/low frequency device (electric motor). The fractional factorial design method was used in the experiment design with sixteen (16) data sets of readings.

Analysis of Variances (ANOVA) was applied to the results from systematic tests. The ANOVA results show that the un-balanced motor vibration frequency did not have the significant impact on the temperature changes in the gasifier simulator. For the fine dust particles testing, the amount of fine dust particles has significant impact to the temperature measurements in the gasifier simulator. The effects of the air and water on the temperature measurements show the same results as reported in the previous report. The ammonia concentration was included as an experimental parameter for the reducing environment in this reporting period. The ammonia concentration does not seem to be a significant factor on the temperature changes.

The linear regression analysis was applied to the temperature reading with five (5) factors. The accuracy of the linear regression is relatively low, which is less than 10% accuracy. Nonlinear regression was also conducted to the temperature reading with the same factors. Since the experiments were designed in two (2) levels, the nonlinear regression is not very effective with the dataset (16 readings). An extra central point test was conducted. With the data of the center point testing, the accuracy of the nonlinear regression is much better than the linear regression.

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1. INTRODUCTION

Gasification is a process that converts carbonaceous materials into combustible gases. The resulting gas is called producer gas or wood gas when fueled by wood. The producer gas of wood gas may be more efficiently converted to high quality energy such as electricity than would be possible by direct combustion of the fuel [1]. Also, corrosive ash elements such as chloride and potassium may be retained by the gasification process, allowing high temperature combustion of the gas from otherwise problematic fuels. The actual gasification usually happens at temperatures above 700^{o}C when the glowing coke is allowed to react with a gasification agent such as oxygen, air or steam. The coke is gradually broken down into gases such as CO, CO_2 and H_2 (from the steam reaction).

Gasification can be applied to all kinds of solid fuels such as coal, low-grade coal, biomass, etc. Fossil fuel and biomass gasification produces a synthesis gas, suitable for conversion to hydrogen, chemicals, fertilizers, or substitute liquid fuels [2, 3]. Fuel gas, synthesis gas, and hydrogen could be used in fuel cells which could further raise the efficiency of power production to the range of 40-50%. Recognizing these benefits, many countries are actively developing biomass gasification technologies for on-site power generation, for co-generation, and for the production of substitute fuel gases [4].

Temperature measurement in the gasifier is always a challenge because of the harsh reducing environment in gasifiers. A reducing environment is the environment that contains alkaline elements and the pH value is greater than 7. In gasifiers, hydrogen and CO are the typical reducing gases in gasifiers. Any feasible instrumentation for temperature measurement in gasifiers will be operated for a long time (at least 150 hours) in an environment, which contains granular carbonaceous material, sticky and/or molten ash and gas containing significant quantities of methane, water vapor, carbon monoxide and hydrogen. Also, low concentrations of alkali metals, hydrogen sulfide, hydrogen chloride and ammonia can be found in the environment. Unfortunately, most available temperature measurement technologies for gasifier are not robust enough to fulfill the requirement of the gasification process [5].

The objective of this research is to develop innovative instrumentation and analysis for high temperature measurements in gasification using the specialized thermocouple along with two cleaning methods. Due to the high cost of building a gasifier for research purposes and/or conducting research on an industrial gasifier, a gasifier simulator is very necessary for conducting effective research at reasonable low cost [6]. Eastman Gasifier Company developed a small-scale gasifier simulator and a computerized gasifier simulator system for research purposes on gasification [7]. These simulators provided very good research data for gasifier research. A gasifier simulator was designed and built at Center for Advanced Energy Systems & Environmental Control Technologies (CAESECT), Morgan State University. This simulator was used along with the proposed temperature measurement device to determine the performance of the temperature measurement device. The systematic test on the clean thermocouple is completed at this reporting period. Five (5) factors are considered as the experimental parameters, which are air flow rate, water flow rate, fine dust particle amount, ammonia addition and high/low frequency vibration device (motor). It is found that the simulator is suitable for the polluted thermocouple tests and the data is ready to be compared with the data of polluted thermocouple testing in the next reporting period. It is also found that the fine dust particle has significant impact to the temperature measurements in the gasifier simulator and the ammonia concentration is not a significant factor affecting the temperature readings in gasifier simulator. In the report, Analysis of Variances (ANOVA) [8], the linear regression and non-linear regression analysis are completed to describe the performance of the gasifier simulator.

2. EXECUTIVE SUMMARY

The systematic tests of the gasifier simulator for the clean thermocouple in the gasifier simulator hot model were completed. Within the systematic tests of this reporting period, five (5) factors were considered as the independent experimental parameters, which were air flow rate, water flow rate, fine dust particle amount, ammonia concentration / addition and high/low frequency vibration device (un-balanced motor). Each experimental parameter had two (2) levels, respectively. The fractional factorial design method was used in the experiment design. Hence, sixteen (16) tests were conducted to determine the effects of these five (5) factors.

Analysis of Variances (ANOVA) was applied to systematic test results. ANOVA was conducted for all individual factors and combined factors. The ANOVA shows that the un-balanced motor vibration frequency did not have the significant impact on the temperature on the temperature reading in the gasifier. It is expected as we planed, so that the vibration method can be applied to clean the thermocouple without affecting the temperature reading. All other factors have some kinds of impacts on the temperature reading on the thermocouple.

As to the amount of the fine dust particle, the data used for the analysis of variance were selected from the steady state conditions. The output of the calculation is using STAT 8.0 software. At the 95% confidence and adjusted R-square of 0.9999, the amount of the fine dust particle has significant impact to the temperature readings in the gasifier simulator since the probability of the fine dust particles is $0.0075<0.05$. The air and water impacts on the temperature measurement remain the same as reported in the previous report.

As to ammonia concentration, ANOVA shows the ammonia concentration's effect on the temperature reading. From six (6) observations of the steady state temperature readings, the correlation coefficient is 0.0131, and the probability of density function is 0.8288. The probability is far more than 0.05. The ammonia concentration is not a significant factor to the temperature readings in the gasifier simulator. There is not much difference in the probability between different concentrations of ammonia addition.

Overall, the fractional factorial design method was used in the experiment design for the systematic tests in this reporting period. The potential factors effecting temperature readings are airflow rate, water flow rate, fine dust particle amount, ammonia addition and high/low frequency vibration device (unbalanced electric motor). The first four factors are basic factors and high/low frequency device is confounded factor. The experimental design reduced the number of experiments in half without losing the accuracy of the systematic tests.

The linear regression was applied to the temperature readings with five (5) factors. The accuracy is relatively low, which is less than 10% accuracy. Nonlinear regression was also conducted to the temperature readings along with the same factors. Since the experiments were designed in two (2) levels, the nonlinear regression does not seem to be very effective with sixteen (16) datasets of readings. An extra central point test was conducted. With the data of the center point testing, the accuracy of the nonlinear regression is much better than the linear regression to predict the data effectively.

3. EXPERIMENTAL

3.1. Gasifier Simulator Systematic Experiment

3.1.1. System Setup

The experimental facilities used in this period were discussed in previous reports and research papers [9-12]. The systematic experiments regarding water injection flow rate and air injection rate were discussed in the previous report III [12]. From the previous results, the air injection rate was a significant factor affecting the temperature reading in the gasifier simulator; the water injection flow rate was not a significant factor affecting the temperature reading. The interaction between water injection rate and air injection rate did not affect the temperature readings in the gasifier simulator.

The other factors, which could have potential effect or interacted effects on the temperature readings, were focused on this progress report. From the literature review conduced earlier, the fine dust particles and the gas flow inside the gasifier could affect the temperature changes while the gasifier is operating at high temperature ranges [3, 6]. The fine dust particle would be melt at this temperature. The melt dust could stick to the thermocouple tips and thus affect the temperature readings. In order to test how the fine dust particle affects the temperature reading, the experiments was designed and conducted in this period.

3.1.2. Temperature Changes with the Fine Dust Particles

The effects of fine dust particles on the temperature changes in the gasifier simulator included the fine dust particle amount and fine dust particle size. These two properties of the fine dust particles were set as variables to determine their influences on the temperature readings. The fine dust particles in the experiment were collected from residue of the char combustion, which was one of the biomass fuels used for gasification. The fine dust particles were categorized into different size ranges using the US Standard Testing Sieve (A.S.T.M. E-11). Specifically, the sizes ranges of 0-75 μm (referred as low level) and 75-150 μm (referred as high level) were used in this experiment as shown in Table 1. As to the amount of the fine dust particle, it was set to low level (0.05Kg) and high level (0.075Kg) as shown in Table 1 as well.

Table 1. The Specification of Fine Dust Particles

Fine dust particle	Low level (-)	High level (+)
Size	0-75 μm	75-150 μm
Amount	0.05 Kg	0.075 Kg

The experiment was designed using the 2^2 full factorial design method [8]. The test matrix is shown in Table 2. The sign of "–" stands for the low level and "+" for high level. The full combination of the two factors consisted of 4 runs of the experiments.

Table 2. Test Matrix of Fine Dust Particle (Size and Amount)

Factors	Size of test particles (μm)	Amount of test particles (Kg)
Run 1	–	–
Run 2	–	+
Run 3	+	–
Run 4	+	+

3.1.3. Test Results of the Experiments

Figure 1 shows the test data of the gasifier hot model simulator including three factors of water, air, and fine dust particles. The detailed test data are shown in Appendix I. The trends of temperature readings for the different sizes of the fine dust particles are similar, but the temperature change rates are different. The temperature change rates are

190 F/min and 220 F/min for the dust size range of 75-150μm and 0-75 μm, respectively, for the first five (5) minutes, and then slow down to the average of 48 F/min and 52 F/min for the period from five to thirty (30) minutes. The temperatures reached the steady state condition while the gasifier is heated up to 90 and 80 minutes, respectively. The stable temperature ranges are 1913 F and 1923 F.

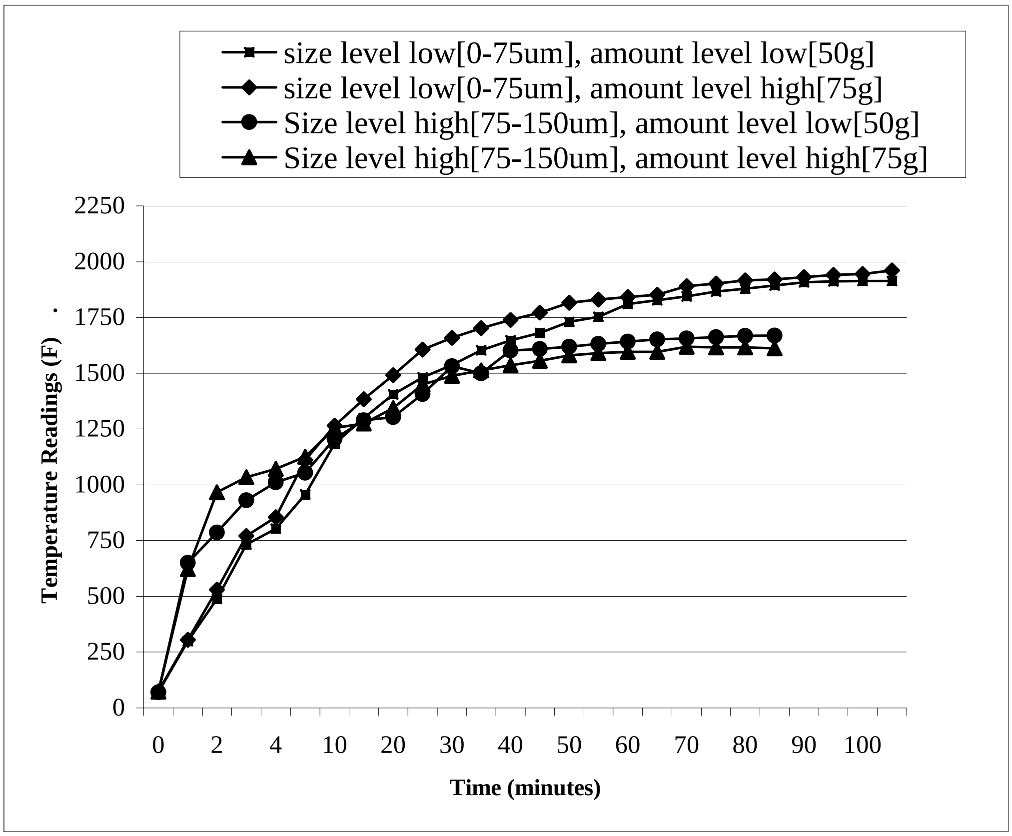

Figure 1. The Temperature Changes With Different Fine Dust Size and Amount
(water flow rate: 0.0033ml/sec; air flow rate: 0.0032 m3/sec)

3.2. Temperature Changes with Reducing Environment

3.2.1. Ammonia Solution Preparation

In this period of experiment, in order to simulate the reducing environment in gasifier, the ammonia hydroxide was added into the gasifier. The specification of ammonia hydroxide is shown in Table 3. The solution was diluted into 5% and 10% before using in experiments. The solution injection device is the same as the water injection.

Table 3. Summary of Ammonia Hydroxide Specification

Appearance	(P.T. Color) 2	Assay	29.58%
Arsenic and Anitomy (as As)	0.010ppm	Carbon Dioxide (CO2)	0.0010%
Chloride (Cl)	0.250ppm	Heavy Metals	0.120ppm
Iron (Fe)	0.010ppm	Residue after Ignition	1.000ppm
Substances Reducing Permanganate	P.T.	Total Sulfur (as SO4)	1.000ppm
Phosphate	0.200ppm	Aluminum	0.030ppm
Calcium	0.057ppm	Boron	0.010ppm
Chromium	0.020ppm	Copper	0.017ppm
Gold	0.030pmm	Zinc	0.030ppm
Lead	0.020ppm	Magnesium	0.030ppm
Manganese	0.020ppm	Nickel	0.010ppm
Potassium	0.030ppm	Titanium	0.03ppm
Tin	0.030ppm	Specific Gravity	-.90

3.2.2. Test Matrix

In order to test the effect of reducing environment on the temperature readings of the gasifier simulator, the test matrix was designed using the factorial design method [8] as shown in Table 4.

Table 4. Test Matrix of Ammonia Hydroxide

Water Flow Rate(ml/ sec)	0.0033	0.0033
Air Flow Rate (m3/sec)	0.0032	0.0032
Ammonia Hydroxide(%)	5	10

3.2.3. Test Results of the Experiments

The test results are shown in Figure 2. The temperature increasing for 5% and 10% of ammonia solution addition are the same pattern. This result indicated that the different concentrations of the solution might have the same effects on the temperature readings. When the time runs up to 70 minutes, these two temperature readings reach to the steady state condition. The detailed test data are shown in Appendix II.

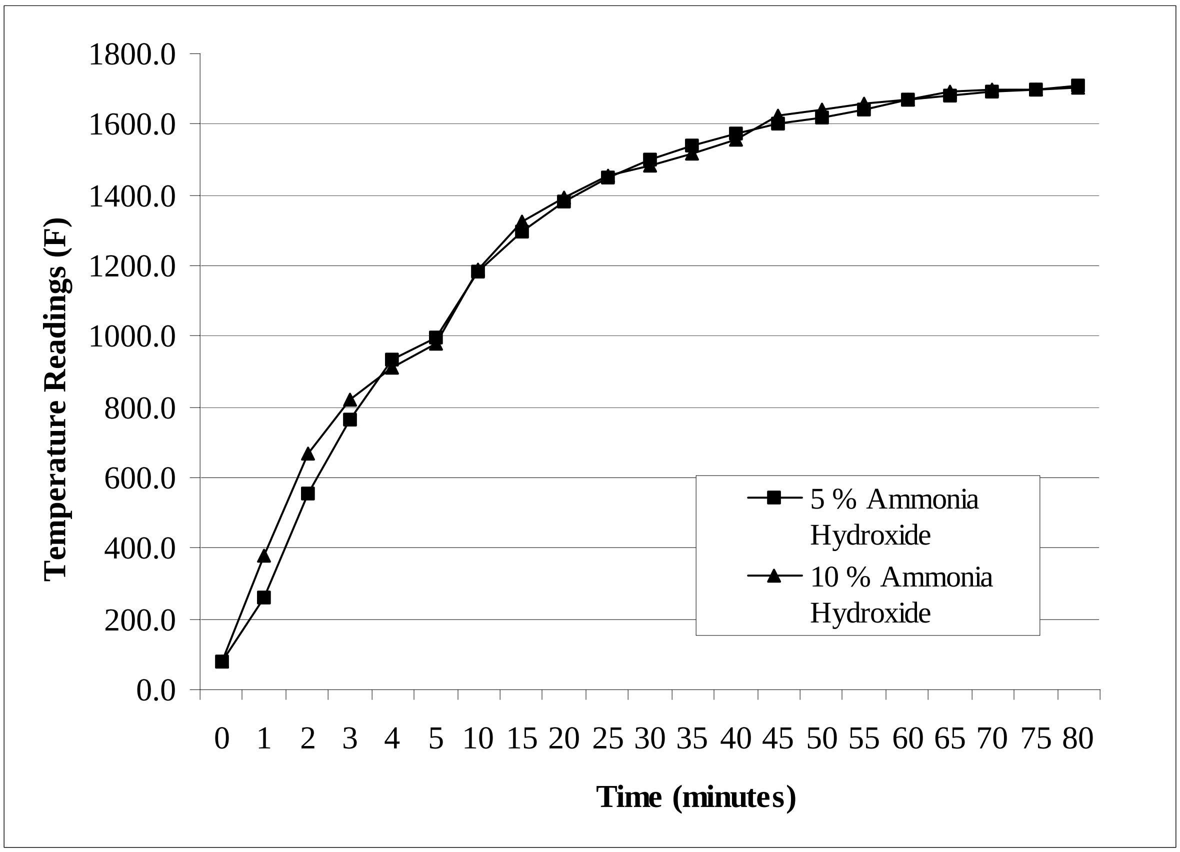

Figure 2. The Temperature Readings with Ammonia Hydroxide Addition
(water flow rate: 0.0033ml/sec ; air flow rate: 0.0032 m3/sec)

4. RESULTS AND DISCUSSION

4.1. The Effect of Fine Dust Particles on the Temperature Changes

The data used for the analysis of variance were selected from the steady state conditions of experiments in section 3.1. The output of the calculation using STATA software is shown in Table 5.

From Table 5, at the 95% confidence and adjusted R-square of 0.9999, the fine dust particles have significant impact to the temperature readings in the gasifier simulator since the probability density function of test particles is 0.0075 which is much less than 0.05. It is believed that the air and water impact on the temperature measurement is the same as previous tests.

Table 5. ANOVA Output of Three Factors Effects on Temperature Readings

Number of obs = 6 R-squared = 1.0000
Root MSE = 2 Adj R-squared = 0.9999

Source	Partial SS	df	MS	F	Prob > F
Model	177951.333	4	44487.8	11121.96	0.0071
air	11236	1	11236	2809.00	0.0120
water	49	1	49	12.25	0.1772
dust	70617.2	2	35308.6	8827.15	0.0075
Residual	4	1	4		
Total	177955.333	5	35591.1		

4.2. Summary of Test Results and Conclusion

The steady state temperature readings were obtained for the statistical analysis. The analysis will determine the effects of different concentrations of the ammonia hydroxide solution on temperature readings as shown in Appendix II. Table 6 shows the steady state condition temperature readings under different ammonia hydroxide concentration.

Table 6. Steady State Condition Temperature Readings under Different Ammonia Concentration

Ammonia Hydroxide Concentration (%)	Temperature Readings (F)
5	1692.7
5	1699.7
5	1707.8
10	1696
10	1700
10	1701

Table 7 shows the Analysis of Variance (ANOVA) of Ammonia hydroxide concentration effects on the temperature readings. From six (6) observations of the steady state temperature readings, the correlation coefficient is 0.0131, and the probability is 0.8288, relatively larger than 0.05. This result means that the concentration does less affect on the temperature readings. There is not much difference between different concentrations of ammonia addition.

Table 7. ANOVA Table of Ammonia Hydroxide (from STATA 8.0 Outputs)

Number of obs = 6 R-squared = 0.0131
Root MSE = 5.66145 Adj R-squared = -0.2336

Source	Partial SS	df	MS	F	Prob > F
Model	1.70661458	1	1.70661458	0.05	0.8288
Concentration	1.70661458	1	1.70661458	0.05	0.8288
Residual	128.208177	4	32.0520443		
Total	129.914792	5	25.9829583		

Footnote: SS—sum square; df—degree of freedom; MS—mean square; F—F-test; Prob—probability density function

4.3. Summary of Overall Systematic Tests Results and Discussion

The overall test matrix is shown in Table 8. The fractional factorial design method was used in the experimental design. The potential factors effecting temperature readings are air flow rate, water flow rate, fine dust particle amount, ammonia concentration and high/low frequency vibration device (motor). The first four factors are considered as basic factors. The high/low frequency un-balanced motor vibration is confounded factor. The levels for each factor are shown in Table 9. The level selection is based on the experiment for single factors.

Table 8. Overall Test Matrix Using Fractional Factorial Design

Factors / Test Run	Air	Water	Dust	Amm-onia	Vibrat-ion	Steady State Mean Temperature Reading (F)
1	–	–	–	–	+	1541.5
2	+	–	–	–	–	1889.5
3	–	+	–	–	–	1615.25
4	+	+	–	–	+	1508.5
5	–	–	+	–	–	1992.8
6	+	–	+	–	+	1572.3
7	–	+	+	–	+	1817.4
8	+	+	+	–	–	1903.86
9	–	–	–	+	–	1891.5
10	+	–	–	+	+	1904.4
11	–	+	–	+	+	1819.8
12	+	+	–	+	–	1863.83
13	–	–	+	+	+	1757
14	+	–	+	+	–	1682
15	–	+	+	+	–	1815.4
16	+	+	+	+	+	1658.4

Table 9. Different Levels for Each Factor

Factor	High level (+)	Low level (–)
Air Flow Rate (m^3/sec)	0.0044	0.0032
Water Flow Rate (ml/sec)	0.0033	0.005
Dust Amount (g)	75	50
Ammonia Hydroxide (%)	10	5
Un-balanced Motor Vibration	With	Without

The overall detailed data are shown in Appendix III. The data shown in Table 10 are selected from the steady state condition of each run. From the ANOVA summary in Table 11, the significant factors could be air flow rate, water flow rate, dust amount addition, and ammonia addition. The un-balanced motor vibration influence is almost negligible. The linear regression model and non-linear regression model were established to illustrate the influences of the significant factors quantitatively.

Table 10. Data for Analysis of Variances

Run	Air	Water	Dust	Ammonia	Vibration*	Temperature (F)
1	0.0032	0.0033	50	5	1	1541.5
2	0.0044	0.0033	50	5	0	1889.5
3	0.0032	0.005	50	5	0	1615.25
4	0.0044	0.005	50	5	1	1508.5
5	0.0032	0.0033	75	5	0	1992.8
6	0.0044	0.0033	75	5	1	1572.3
7	0.0032	0.005	75	5	1	1817.4
8	0.0044	0.005	75	5	0	1903.86
9	0.0032	0.0033	50	10	0	1891.5
10	0.0044	0.0033	50	10	1	1904.4
11	0.0032	0.005	50	10	1	1819.8
12	0.0044	0.005	50	10	0	1863.83
13	0.0032	0.0033	75	10	1	1757
14	0.0044	0.0033	75	10	0	1682
15	0.0032	0.005	75	10	0	1815.4
16	0.0044	0.005	75	10	1	1658.4

* 1—with motor vibration, 0—without motor vibration.

Table 11. ANOVA Table for Overall Tests Results

Number of obs = 16   R-squared = 0.3015

Root MSE = 152.689   Adj R-squared = -0.0477

Source	Partial SS	df	MS	F	Prob > F
Model	100643.646	5	20128.7292	0.86	0.5375
air	4484.31482	1	4484.31482	0.19	0.6703
water	3264.98127	1	3264.98127	0.14	0.7160
dust	1699.09102	1	1699.09102	0.07	0.7927
ammonia	18990.216	1	18990.216	0.81	0.3880
motor	72205.0431	1	72205.0431	3.10	0.1089
Residual	233139.208	10	23313.9208		
Total	333782.854	15	22252.1903		

Footnote: SS—sum square; df—degree of freedom; MS—mean square; F—F-test; Prob—probability density function

4.4. Regression Analysis and Modeling

4.4.1. Linear Regression Model

The general multiple linear regression statistical equation is [13,14]:

$$y = E(y) + \varepsilon \qquad (1)$$

Where E(y) is predicted value or empirical model for dependent variable, that is, temperature. ε is error term.

The assumptions for the multiple regression analysis are: the mean of ε is 0 with a normal distribution, this implies that the mean of y is equivalent to the deterministic component of the model; for all setting of the independent variables x_i, the variance of ε is constant; the random errors are independent. So the linear empirical model can be written as:

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \qquad (2)$$

The Least Square Method can be used in minimizing the estimates of β_0, β_1,… β_k. The sums square of error is expressed as follows:

$$SSE = \sum (y_i - \widehat{y}_i)^2 = \sum [y_i - (\widehat{\beta}_0 + \widehat{\beta}_1 x_{1i} + \widehat{\beta}_2 x_{2i} + \cdots + \widehat{\beta}_k x_{ki})]^2 \qquad (3)$$

To obtain the minimization of the SSE, the partial derivatives of SSE to the variables β_0, β_1,… β_k,

$$\frac{\partial SSE}{\partial \widehat{\beta}_0} = 0, \quad \frac{\partial SSE}{\partial \widehat{\beta}_1} = 0, \quad \cdots, \quad \frac{\partial SSE}{\partial \widehat{\beta}_k} = 0 \qquad (4)$$

The development of above equations is as follows:

$$\left.\begin{array}{l}
(\sum x_{1i})\widehat{\beta}_0 + (\sum x_{1i})^2 \widehat{\beta}_1 + (\sum x_{1i} x_{2i})\widehat{\beta}_2 + \cdots + (\sum x_{1i} x_{ki})\widehat{\beta}_k = \sum x_{1i} y_i \\
(\sum x_{2i})\widehat{\beta}_0 + (\sum x_{1i} x_{2i})\widehat{\beta}_1 + (\sum x_{2i})^2 \widehat{\beta}_2 + \cdots + (\sum x_{2i} x_{ki})\widehat{\beta}_k = \sum x_{2i} y_i \\
\quad \cdot \\
\quad \cdot \\
\quad \cdot \\
(\sum x_{ki})\widehat{\beta}_0 + (\sum x_{1i} x_{ki})\widehat{\beta}_1 + \quad \cdots \quad + (\sum x_{ki})^2 \widehat{\beta}_k = \sum x_{ki} y_i
\end{array}\right\} (5)$$

The data matrix Y, X, the $\widehat{\beta}$ matrix and the error matrix:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{11} & x_{21} \cdots & x_{k1} \\ 1 & x_{12} & x_{22} \cdots & x_{k2} \\ \cdot & & & \\ \cdot & & & \\ 1 & x_{1n} & x_{2n} \cdots & x_{kn} \end{bmatrix} \quad \widehat{\beta} = \begin{bmatrix} \widehat{\beta}_0 \\ \widehat{\beta}_2 \\ \cdot \\ \cdot \\ \widehat{\beta}_n \end{bmatrix} \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdot \\ \cdot \\ \varepsilon_n \end{bmatrix} \quad (6)$$

The general linear model can be expressed in matrix form as:

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \qquad (7)$$

The software STATA 8.0 was used in getting the linear empirical model. The result is shown in Table 12.

According to the software output, the linear regression model could be addressed as follows:

$$Y_{temperature}=1732.043-27902.09\,V_a-611.7774V_w+0.8244M_d+13.7805M_a \quad (8)$$

Where: V_a stands for air flow rate (m^3/sec), V_w water flow rate (ml/sec), dust amount (g), and ammonia addition concentration (%).

The linear regression model deterministic, R-squared = 0.0852, is relatively low. This result is believed that the linear regression model is not appropriate choice for the temperature prediction. In this research period, the non-linear model was also used in the prediction of the temperature inside the gasifier simulator.

Table 12. The Linear Regression Output

<table>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>F(4, 11) = 0.26</td></tr>
<tr><td>Model</td><td>28438.6031</td><td>4</td><td>7109.65078</td><td></td><td></td><td>Prob > F = 0.8999</td></tr>
<tr><td>Residual</td><td>305344.251</td><td>11</td><td>27758.5683</td><td></td><td></td><td>R-squared = 0.0852</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Adj R-squared = -0.2475</td></tr>
<tr><td>Total</td><td>333782.854</td><td>15</td><td>22252.1903</td><td></td><td></td><td>Root MSE = 166.61</td></tr>
<tr><td>temperature</td><td>Coef.</td><td>Std. Err.</td><td>t</td><td>P>|t|</td><td>[95% Conf.</td><td>Interval]</td></tr>
<tr><td>Source</td><td>SS</td><td>df</td><td>MS</td><td></td><td></td><td>Number of obs = 16</td></tr>
<tr><td>air</td><td>-27902.09</td><td>69420.43</td><td>-0.40</td><td>0.695</td><td>-180695.4</td><td>124891.2</td></tr>
<tr><td>water</td><td>-611.7774</td><td>1783.823</td><td>-0.34</td><td>0.738</td><td>-4537.944</td><td>3314.389</td></tr>
<tr><td>dust</td><td>.8244006</td><td>3.332181</td><td>0.25</td><td>0.809</td><td>-6.509679</td><td>8.158481</td></tr>
<tr><td>ammonia</td><td>13.7805</td><td>16.6609</td><td>0.83</td><td>0.426</td><td>-22.8899</td><td>50.4509</td></tr>
<tr><td>_cons</td><td>1732.043</td><td>364.103</td><td>4.76</td><td>0.001</td><td>930.6578</td><td>2533.428</td></tr>
</table>

Footnote: SS—sum square; df—degree of freedom; MS—mean square; F—F-test; Prob—probability density function

4.4.2. Non-linear Regression Model

Nonlinear regression is to deal with the case that linear regression has relatively low accuracy [13,14].

Polynomial regression is a typical regression that deals with non-linear data set. A simple polynomial regression could be described as follows: Polynomials are a special case of the more general non-linear models. For data that are shaped like a parabola, a quadratic model ($Y <= X \ X^2$) could be sufficient. If the curve is trends up again at one end, a cubic model might be necessary. Curves with multiple kinks need even higher-order terms. When fitting a model like $Y <= X \ X^2$, the STATA program finds the best quadratic curve to fit the data. In other words, it will find the best values for the coefficients (or parameters) ‘a’, ‘b’ and ‘c’ in the equation $Y = a + bX + cX^2$. The value of ‘a’ represents the overall position of the curve along the Y axis; for example, an increase of 1 unit in ‘a’ shifts the whole curve up the Y axis by 1 unit. The value of ‘b’ represents the amount of overall upward or downward linear (straight-line) trend in the values of Y along the X axis; in other words, if someone draws a straight line to fit all the points well, ‘b’ is the slope of the line, which is the same thing as the increase (or decrease, if ‘b’ is negative) in Y for each 1-unit increase in X. For all the data, ‘b’ would represent the change in attitude per year of experience. The value of ‘c’ represents the amount of curvature in the data.

The knowledge-based regression analysis is the method that transforms the variables to non-linear forms with the consideration of physics or engineering terms. The key part in the knowledge-based regression is to determine the mask functions of the independent variables. These mask functions transfers independent variables into nonlinear variables. Theoretically, this approach shall provide relatively high accuracy model for the experimental data. However, how to obtain the mask function largely depends on the researcher's experience and method of try and error.

Different from the linear regression, the non-linear regression needs more than two (2) levels for each input factor. In order to regress the non-linear model more accuracy, the central point of each input factors were tested and extra data were added to the overall test matrix as shown in Table 13.

Table 13 The Overall Testing Data for Non-linear Regression Analysis

Run Number	Air (ml/sec)	Water (m^3/sec)	Dust (g)	Ammonia (%)	Vibration*	Temperature (F)
1	0.0032	0.0033	50	5	1	1541.5
2	0.0044	0.0033	50	5	0	1889.5
3	0.0032	0.005	50	5	0	1615.25
4	0.0044	0.005	50	5	1	1508.5
5	0.0032	0.0033	75	5	0	1992.8
6	0.0044	0.0033	75	5	1	1572.3
7	0.0032	0.005	75	5	1	1817.4
8	0.0044	0.005	75	5	0	1903.86
9	0.0032	0.0033	50	10	0	1891.5
10	0.0044	0.0033	50	10	1	1904.4
11	0.0032	0.005	50	10	1	1819.8
12	0.0044	0.005	50	10	0	1863.83
13	0.0032	0.0033	75	10	1	1757
14	0.0044	0.0033	75	10	0	1682
15	0.0032	0.005	75	10	0	1815.4
16	0.0044	0.005	75	10	1	1658.4
17	0.0038	0.00415	62.5	7.5	0	1494
18	0.0038	0.00415	62.5	7.5	0	1492
19	0.0038	0.00415	62.5	7.5	0	1484
20	0.0038	0.00415	62.5	7.5	0	1488

* 0=without un-balanced motor vibration; 1=with un-balanced motor vibration

Table 14 shows the non-linear regression output for temperature prediction of this gasifier system using statistical software SPSS 10.0. The Non-linear regression model is shown in Equation 9. The R-square is 0.65328, which means the temperature inside the gasifier is well determined by the non-linear regression model.

$$Y_{Temperature}=1600+3424.95*V_a-125.46*(V_a)^2-3772.7*V_w+125.96*V_w^2 -7883.56*M_d+c44*\sin(M_d)**2+867.02*M_a-46.67*M_a^2 +0.60*V_w*M_a-2.60*M_d*M_a \quad (9)$$

Table 14. The Summary of Nonlinear Regression Statistics

Source	DF	Sum of Squares	Mean Square
Regression	10	58829019.6531	5882901.96531
Residual	10	199709.08792	19970.90879
Uncorrected Total	20	59028728.7410	
(Corrected Total)	19	576000.27732	

R squared = 1 - Residual SS / Corrected SS = .65328

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval Lower	Upper
C1	3424.9520607	1004598407.7	-2238381318	2238388167.8
C2	-125.4642826	36772674.350	-81934749.88	81934498.947
C3	-3772.768455	4.55317E+16	-1.01451E+17	1.01451E+17
C4	125.95679755	1.52382E+15	-3.39528E+15	3.39528E+15
C5	46.010634580	1.03813E+16	-2.31310E+16	2.31310E+16
C6	-7883.559354	3.18313E+18	-7.09245E+18	7.09245E+18
C7	867.02282261	7.77456E+15	-1.73228E+16	1.73228E+16
C8	-46.66238657	5.18304E+14	-1.15485E+15	1.15485E+15
C9	.601470588	5.005088409	-10.55056135	11.753502530
C10	-2.596680000	55085185.289	-122737444.1	122737438.92

5. CONCLUSIONS:

The major accomplishments in this semi-annual period are listed below:

1. The screening tests for the significant input factors upon the temperature readings are being successfully conducted during this reporting period.
2. ANOVA analysis is a very efficient statistical method to analyze the experimental results and data
3. The mathematical and statistical models for the temperature readings are established using the linear and non-linear regression methods, respectively.
4. The amount of fine dust particles has a significant effect to the temperature measurements. The temperature increases at steady state along with the increase of the amount of the fine dust particle.
5. The reducing environment in the gasifier simulator has a significant effect on the temperature readings. The temperature readings at steady state increase along with the increase of concentration of the ammonia hydroxide.
6. The overall tests matrix has been accomplished based on the central point fractional factorial design. The significant factors for temperature readings in the gasifier simulator are dust, water, air, and ammonia. The un-balanced motor vibration is proved to be a non-significant factor.
7. The linear and non-linear regression methods are very effective in modeling of the mathematical function
8. Non-linear regression approach is proved to be more accurate than the linear regression in this modeling process.

6. RESEARCH CONTINUATION:

The ongoing research is on the schedule. The continuation of the research will include temperature measurement with the contaminated thermal couple and comparison analysis. A site visit/discussion to an ultrasonic transducer manufacturing company is scheduled by the end of October 2004. The thermocouple assembly will be taken to the company to identify the vibration performance of the thermocouple assembly. The high frequency vibration device and clean method will be applied after the site visit/discussion.

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Appendix I. Test Data of Dust particle size and amount in the Gasifier Hot Model Simulator System

Reading Time (minutes)	Water Flowrate: 0.0033ml/sec			
	Air Flowrate: 0.0032 m3/sec			
	Dust Amount: 75g		Dust Amount: 50g	
	Dust Size: 75-150μm	Dust Size: 0-75μm	Dust Size: 75-150μm	Dust Size: 0-75μm
	Temperature Reading (F)	Temperature Reading (F)	Temperature Reading (F)	Temperature Reading (F)
0	72	74.4	69.9	73
1	300	305	650.9	621.9
2	489	529.4	785.6	967
3	732	770.8	930.8	1034
4	804	855.4	1011	1072
5	957	1111	1054	1126
10	1185	1265	1206	1255
15	1299	1383	1289	1274
20	1405	1491	1304	1343
25	1481	1606	1406	1450
30	1537	1659	1531	1488
35	1602	1702	1500	1513
40	1647	1739	1601	1535
45	1680	1772	1609	1556
50	1730	1816	1619	1580
55	1753	1831	1632	1590
60	1810	1842	1641	1596
65	1827	1852	1651	1595
70	1844	1891	1656	1619
75	1866	1902	1661	1616
80	1879	1917	1667	1615
85	1893	1920	1669	1611
90	1907	1930		
95	1912	1940		
100	1913	1945		
105	1914	1960		

Appendix II. The Test Results with Ammonia Solution Addition

	Ammonia solution	
	5%	10%
Time	Temperature (F)	Temperature (F)
0	77.3	81.6
1	260.5	376.7
2	552.0	669.3
3	764.6	818.9
4	935.3	913.7
5	999.0	980.1
10	1184.7	1186.3
15	1298.0	1325.3
20	1381.3	1392.3
25	1448.5	1454.0
30	1497.7	1484.0
35	1540.5	1515.0
40	1572.8	1556.3
45	1601.3	1624.7
50	1620.3	1642.3
55	1641.8	1656.3
60	1667.0	1672.3
65	1682.7	1689.7
70	1692.7	1696.0
75	1699.7	1700.0
80	1707.8	1701.0

Appendix III. Overall Test Results using Fractional Factorial Design

Date	6-Jul	3-Jun	27-May	8-Jun	5-Aug	6-Aug	12-Aug	10-Aug	3-May	7-May	12-Jul	22-Jul	16-Aug	23-Aug	27-Jul	18-Aug
Location	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105
Ambient Temp(F)	81.2	70.9	73	73.6	82.9	81.6	74	70.9	70.8	71	73.7	72	81.3	81.6	73.8	82
Air Flow Rate Level	–	+	–	+	–	+	–	+	–	+	–	+	–	+	–	+
Water Flow Rate Level	–	–	+	+	–	–	+	+	–	–	+	+	–	–	+	+
Fine Dust Level	–	–	–	–	+	+	+	+	–	–	–	–	+	+	+	+
Ammonia Level	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	+
Vibration Level	+	–	–	+	–	+	+	–	–	+	+	–	+	–	–	+
Time	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)	T (F)
0	81	71	73	74	83	82	74	71	71	71	74	72	81	82	74	82
1	128	754	622	391	110	377	340	218	750	760	340	550	370	377	339	383
2	655	897	967	655	319	597	655	433	890	898	655	777	718	654	654	636
3	887	993	1034	809	671	845	845	536	991	996	841	919	858	797	840	802
4	984	1046	1072	913	1101	958	970	690	1045	1050	970	1010	947	890	966	904
5	1018	1105	1126	976	1164	1015	1049	774	1110	1110	1049	1080	1005	958	1047	977
10	1157	1234	1255	1156	1280	1190	1280	1047	1229	1240	1280	1260	1214	1175	1278	1170
15	1234	1381	1274	1232	1434	1290	1378	1221	1380	1389	1379	1384	1400	1299	1377	1277
20	1296	1495	1343	1289	1544	1349	1465	1350	1490	1500	1459	1480	1457	1371	1460	1349
25	1345	1564	1450	1341	1615	1374	1550	1471	1560	1569	1546	1558	1568	1410	1545	1384
30	1379	1620	1488	1377	1680	1393	1603	1555	1615	1630	1603	1617	1585	1445	1602	1422
35	1411	1689	1513	1407	1736	1415	1655	1620	1689	1795	1655	1725	1625	1480	1654	1440
40	1433	1738	1535	1431	1781	1429	1693	1671	1737	1740	1693	1717	1648	1501	1692	1520
45	1454	1770	1556	1448	1823	1438	1720	1725	1769	1781	1723	1752	1726	1579	1720	1569

Overall Test Results using Fractional Factorial Design (*Contd.*)

50	1472	1807	1580	1461	1850	1438	1745	1757	1809	1810	1745	1778	1730	1617	1744	1580
55	1485	1831	1590	1474	1875	1450	1767	1801	1832	1840	1767	1804	1736	1635	1766	1598
60	1493	1843	1526	1480	1898	1525	1793	1813	1840	1846	1794	1820	1748	1662	1793	1607
65	1503	1872	1595	1493	1920	1545	*1806*	1834	1872	1880	*1802*	1841	*1754*	*1681*	1801	1634
70	1509	1877	*1619*	*1503*	1937	1558	*1810*	1840	1879	*1895*	*1806*	1851	*1759*	*1683*	*1809*	1646
75	1515	*1886*	*1616*	*1503*	1951	*1569*	*1815*	1848	1883	*1890*	*1815*	1853	*1757*	*1682*	*1812*	*1661*
80	1523	*1891*	*1615*	*1510*	1965	*1574*	*1820*	1860	*1890*	*1901*	*1820*	*1861*	*1758*	Stop	*1815*	*1660*
85	1528	*1890*	*1611*	*1511*	1975	*1574*	*1819*	1868	*1892*	*1905*	*1823*	*1864*	Stop		*1819*	*1662*
90	1532	*1891*	Stop	*1507*	*1986*	Stop	*1823*	1881	*1894*	*1910*	*1824*	*1867*			*1822*	*1663*
95	*1538*	Stop		*1506*	*1990*		Stop	*1890*	*1890*	*1914*	*1817*	Stop			Stop	Stop
100	*1541*			Stop	*1994*			*1895*	Stop	*1916*	Stop					
105	*1542*				*1996*			*1900*		Stop						
110	*1545*				*1998*			*1904*								
115	Stop				Stop			*1910*								
120								*1916*								
125								*1912*								
								Stop								
Steady State Mean Temperature (F)	1541.5	1889.5	1615.25	1508.5	1992.8	1572.3	1817.4	1903.86	1891.5	1904.4	1819.8	1863.83	1757.0	1682	1815.4	1658.4