

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

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ABSTRACT

During this reporting period, the literature survey including the gasifier temperature measurement literature, the ultrasonic application and its background study in cleaning application, and spray coating process are completed. The gasifier simulator (cold model) testing has been successfully conducted. Four factors (blower voltage, ultrasonic application, injection time intervals, particle weight) were considered as significant factors that affect the temperature measurement. The Analysis of Variance (ANOVA) was applied to analyze the test data. The analysis shows that all four factors are significant to the temperature measurements in the gasifier simulator (cold model). The regression analysis for the case with the normalized room temperature shows that linear model fits the temperature data with 82% accuracy (18% error). The regression analysis for the case without the normalized room temperature shows 72.5% accuracy (27.5% error). The nonlinear regression analysis indicates a better fit than that of the linear regression. The nonlinear regression model's accuracy is 88.7% (11.3% error) for normalized room temperature case, which is better than the linear regression analysis. The hot model thermocouple sleeve design and fabrication are completed. The gasifier simulator (hot model) design and the fabrication are completed. The system tests of the gasifier simulator (hot model) have been conducted and some modifications have been made. Based on the system tests and results analysis, the gasifier simulator (hot model) has met the proposed design requirement and is ready for system test. The ultrasonic cleaning method is under evaluation and will be further studied for the gasifier simulator (hot model) application. The progress of this project has been on schedule.

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1. INTRODUCTION

1.1 Background

It is well known that gasification offers the cleanest, most efficient method available to produce synthesis gas from low or negative-value carbon-based feed stocks such as coal, petroleum coke, high sulfur fuel oil or materials that would otherwise be disposed as waste[1]. The gas can be used in place of natural gas to generate electricity or as a basic raw material to produce chemicals and liquid fuels.

All the operating gasifiers are equipped with temperature instrumentation. Normally, the regular temperature measurement techniques such as heat expansion thermometers and regular thermocouples are used in these gasifiers. However, temperature measurement in gasification is always a problem because the current methods are not robust and reliable in the harsh gasifiers environment. Based on the DOE Gasification Database Results Update 2001 [2,3], there are more than 800 gasifiers operating in the United States. Most of them suffer from unreliable temperature measurement, which can trigger false alarms, lower the gas quality and create accidents. Since most of the existing and planned gasifiers are used to or will be used to generate electricity in IGCC, cost rules similar to those used for power plants can be applied to the operation of these 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.

Because of the harsh environment in gasifiers and the high cost of developing temperature measurement device on a full scale gasifier, a feasible approach normally starts with a small scale cold model. The cold model testing shall provide tremendous information at a much lower cost. After the cold model tests are successfully completed, a hot model shall be made to test the temperature measurement device. These hot model tests shall provide the accurate results of the temperature measurement device that could be sued directly into the full-scale testing. The cold model and hot model tests are the most cost efficient way to study or develop applications in a full-scale unit.

The objective of this research is to develop innovative instrumentation and analysis for high temperature measurement in gasification using the specialized thermocouple along with two cleaning methods. Basically, ultrasonic dirt peeling and high-pressure oxygen injection cleaning are the two methods proposed to clean the thermocouple tip for accurate and robust measurement. The anti-erosion/corrosion coating sprayed on the thermocouple could make the thermocouple specialized and unique. The proposed instrumentation is believed to be low-cost and reliable. Finally, this research work is expected to reduce a significant amount of the operation/maintenance costs and increase the gas production rate.

In order to develop the proposed instrumentation successfully, it is essential to design a corresponding cold gasification model to test the proposed instrumentation. The cold model can help to determine some important factors before the hot model tests are scheduled [4].

1.2 Literature Review

The literature survey focuses on the following categories.

a. Gasification and Gasifiers

The gasification process converts any carbon-containing material into a synthesis gas composed primarily of carbon monoxide and hydrogen, which can be used as a fuel to generate electricity or steam or used as a basic chemical building block for a large number of uses in the petrochemical and refining industries [5]. Gasification adds value to low- or negative-value feed stocks by converting them to marketable fuels and products.

Gasification technologies differ in many aspects but share certain general production characteristics. Typical raw materials used in gasification are coal, petroleum based materials (crude oil, high sulphur fuel oil, petroleum coke, and other refinery residuals), gases, or materials that would otherwise be disposed of as waste. The feedstock is prepared and fed to the gasifier. The feedstock reacts in the gasifier with steam and oxygen at high temperature and pressure in a reducing (oxygen starved) atmosphere. This produces the synthesis gas, or syngas, made up primarily of carbon monoxide and hydrogen (more than 85% by volume) and smaller quantities of carbon dioxide and methane. The high temperature in the gasifier converts the inorganic materials in the feedstock (such as ash and metals) into a vitrified material resembling coarse sand. With some feedstocks, valuable metals are concentrated and recovered for reuse. The vitrified material, generally referred to as slag, is inert and has a variety of uses in the construction and building industries.

There are various kinds of gasifiers available in the market. Among them, air-blown fixed-bed and fluidized-bed gasifiers appear to have several advantages for biomass power systems [6]. The oxidant for the gasification process can be either atmospheric air or pure oxygen. Oxygen-blown gasifiers offer a higher-Btu gas and faster reaction rates than air-blown systems, but have the disadvantage of additional capital costs associated with the oxygen plant.

b. Erosion and Corrosion in Gasifiers

Many potential biomass feedstocks, such as straw and many fast-growing energy crops as well as industrial and municipal waste fuels often contain high amounts of chlorine, and alkali metals or aluminum, which have a tendency to cause severe corrosion and fouling problems in boiler [7,8].

Corrosion may be a problem, especially on surfaces in the high temperature areas of the gasifier (the throat). These corrosions can be caused by too high temperatures and/or contaminants in the feedstock. The gasifier design should be adapted to lower the temperature and/or to use other heat resistant materials. Before the producer gas can be used in a gas engine or turbine, it has to be cooled and cleaned from tars, alkaline metals and dust. Tars may condensate on valves and fittings hampering the valves to function properly; alkaline metals, dust and tars cause corrosion and erosion of cylinder walls and pistons. When the gas is used in a heat applications the requirements on gas quality are not that strict, especially when the gas remains at high temperatures during transportation to the burner, which prevents tars and alkaline metals to condensate.

c. Current Temperature Measurement in Gasifiers

Thermocouples are used in the gasifiers to measure the temperature. The big challenge is how to keep the sight ports clean [9,10]. Reliable measurement of gasifier reaction chamber temperature is important for the proper operation of slagging, entrained-flow gasification processes. Historically, thermocouples have been used as the main measurement technique, with the temperature inferred from syngas methane concentration being used as a backup measurement. While these have been sufficient for plant operation in many cases, both techniques suffer from limitations. The response time of methane measurements is too slow to detect rapid upset conditions and thermocouples are subject to long-term drift, as well as slag attack, which eventually leads to failure of the thermocouple. Texaco's Montebello Technology Center (MTC) has developed an infrared ratio pyrometer system for measuring gasifier reaction chamber temperature. This system has a faster response time than both methane and thermocouples, and has been demonstrated to provide reliable temperature measurements for longer periods of time when compared to thermocouples installed in the same MTC gasifier. In addition, the system can be applied to commercial gasifiers without any significant scale-up problems. The major equipment items, the purge system and the safety shutdown system in a commercial plant will be essentially identical to the prototypes at MTC.

d. Ultrasonic Cleaning

Ultrasonic cleaning involves the use of high-frequency sound waves (above the upper range of human hearing, or about 18 kHz) to remove a variety of contaminants from parts immersed in aqueous media [11]. The contaminants can be dirt, oil, grease, buffing/polishing compounds, and mold release agents, just to name a few. Materials that can be cleaned include metals, glass, ceramics, and so on.

In a process termed cavitation, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a solution. The bubbles subjected to these alternating pressure waves continue to grow until they reach resonant size. Just prior to the bubble implosion, there is a tremendous amount of energy stored inside the bubble itself.

Temperature inside a cavitating bubble can be extremely high, with pressures up to 500 atm. The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km/hr toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate. Because of the inherently small size of the jet and the relatively large energy, ultrasonic cleaning has the ability to reach into small crevices and remove entrapped soils very effectively.

An excellent demonstration of this phenomenon is to take two flat glass microscope slides, put lipstick on a side of one, place the other slide over top, and wrap the slides with a rubber band. When the slides are placed into an ultrasonic bath with nothing more than a mild detergent and hot water, within a few minutes the process of cavitation will work the lipstick out from between the slide assembly. It is the powerful scrubbing action and the extremely small size of the jet action that enable this to happen.

In order to produce the positive and negative pressure waves in the aqueous medium, a mechanical vibrating device is required. Ultrasonic manufacturers make use of a diaphragm attached to high-frequency transducers. The transducers, which vibrate at their resonant frequency due to a high-frequency electronic generator source, induce amplified vibration of the diaphragm. This amplified vibration is the source of positive

and negative pressure waves that propagate through the solution in the tank. The operation is similar to the operation of a loudspeaker except that it occurs at higher frequencies. When transmitted through water, these pressure waves create the cavitation processes.

The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. Typically, ultrasonic transducers used in the cleaning industry range in frequency from 20 kHz to 80 kHz. The lower frequencies create larger bubbles with more energy, as can be seen by dipping a piece of heavy-duty aluminum foil in a tank. The lower-frequency cleaners will tend to form larger dents, whereas higher-frequency cleaners form much smaller dents.

The basic components of an ultrasonic cleaning system include a bank of ultrasonic transducers mounted to a radiating diaphragm, an electrical generator, and a tank filled with aqueous solution. A key component is the transducer that generates the high-frequency mechanical energy. There are two types of ultrasonic transducers used in the industry, piezoelectric and magnetostrictive. Both have the same functional objective, but the two types have dramatically different performance characteristics.

The ultrasonic generator converts a standard electrical frequency of 60 Hz into the high frequencies required in ultrasonic transmission, generally in the range of 20 kHz to 80 kHz. Many of the better generators today use advanced technologies such as sweep frequency and autofollow circuitry. Frequency sweep circuitry drives the transducers between a bandwidth slightly greater and slightly less than the center frequency. For example, a transducer designed to run at 30 kHz will be driven by a generator that sweeps between 29 kHz and 31 kHz. This technology eliminates the standing waves and hot

spots in the tank that are characteristic of older, fixed-frequency generators. Autofollow circuitry is designed to maintain the center frequency when the ultrasonic tank is subjected to varying load conditions. When parts are placed in the tank or when the water level changes, the load on the generator changes. With autofollow circuitry, the generator matches electrically with the mechanical load, providing optimum output at all times to the ultrasonic tank.

The safety issues for the ultrasonic application are also under investigation. Human exposure to ultrasonic with frequencies between 16 kHz and 100 kHz can be divided into three distinct categories: airborne conduction, direct contact through a liquid coupling medium, and direct contact with a vibrating solid.

Ultrasonic through airborne conduction does not appear to pose a significant health hazard to humans. However, exposure to the associated high volumes of audible sound can produce a variety of effects, including fatigue, headaches, nausea and tinnitus. When ultrasonic equipment is operated in the laboratory, the apparatus must be enclosed in a 2-cm thick wooden box or in a box lined with acoustically absorbing foam or tiles to substantially reduce acoustic emissions (most of which are inaudible).

Direct contact of the body with liquids or solids subjected to high-intensity ultrasonic of the sort used to promote chemical reactions should be avoided. Under sonochemical conditions, cavitation is created in liquids, and it can induce high-energy chemistry in liquids and tissues. Cell death from membrane disruption can occur even at relatively low acoustic intensities.

Exposure to ultrasonically vibrating solids, such as an acoustic horn, can lead to rapid frictional heating and potentially severe burns.

e. High Velocity Oxygen Flame Process Concept

The High Velocity Oxygen Flame (HVOF) coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes [12]. HVOF Spraying is essentially a variation of powder flame spraying in which a modified torch is used to constrict the gas flow. This produces an extremely high velocity flame that is similar to that of a jet engine. HVOF coatings are usually denser and have higher bond strengths than coatings produced by other processes. This is particularly useful when tough, wear resistant coatings, such as tungsten carbide, are required.

The HVOF thermal spray process is basically the same as the combustion powder spray process except that this process has been developed to produce extremely high spray velocity. There are a number of HVOF guns which use different methods to achieve high velocity spraying. One method is basically a high pressure water cooled HVOF combustion chamber and long nozzle. Fuel (kerosene, acetylene, propylene and hydrogen) and oxygen are fed into the chamber, combustion produces a hot high pressure flame which is forced down a nozzle increasing its velocity. Powder may be fed axially into the HVOF combustion chamber under high pressure or fed through the side of laval type nozzle where the pressure is lower. Another method uses a simpler system of a high pressure combustion nozzle and air cap. Fuel gas (propane, propylene or hydrogen) and oxygen are supplied at high pressure, combustion occurs outside the nozzle but within an air cap supplied with compressed air. The compressed air pinches and accelerates the flame and acts as a coolant for the HVOF gun. Powder is fed at high pressure axially from the center of the nozzle.

The coatings produced by HVOF are similar to those produce by the detonation process. HVOF coatings are very dense, strong and show low residual tensile stress or in some cases compressive stress, which enable very much thicker coatings to be applied than previously possible with the other processes [12].

The very high kinetic energy of particles striking the substrate surface do not require the particles to be fully molten to form high quality HVOF coatings. This is certainly an advantage for the carbide cermet type coatings and is where this process really excels.

HVOF coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes. New applications, previously not suitable for thermal spray coatings are becoming viable.

f. Design of Experiments

Experimental design methods have found broad application in many disciplines [13]. In fact, experimentation can be viewed as part of the scientific process and as one of the ways to reveal how systems or processes work.

Experimental design is a critically important tool in the engineering world for improving the performance of a manufacturing process. It also has extensive application in the development of new processes [13]. The application of experimental design techniques early in process development can result in:

1. Improved process yields.
2. Reduced variability and closer conformance to nominal or target requirements.
3. Reduced developmental time.
4. Reduced overall cost.

2. EXECUTIVE SUMMARY

The literature survey was completed during this reporting period. The literatures related to the gasifier temperature measurement show the problems associated with the current temperature measurement techniques, as well as the advantage/disadvantage of the current temperature measurement techniques. The literature survey of the ultrasonic cleaning application shows that the liquid-based ultrasonic cavitation is not applicable to the proposed temperature measurement technique. However, the literatures show that the ultrasonic welding concept could be used to the proposed temperature measurement technique. The literatures related to spray coating process show that the HVOF at low spray temperature is safe to the thermocouple assembly, and also, the HVOF shall increase the corrosion/erosion resistance of the coated objection in either oxidized or reducing environments.

The gasifier simulator (cold model) testing has been successfully finished. Four (4) factors including blower voltage, ultrasonic application, injection time intervals, and particle weight, were considered as the significant factors that affect the temperature measurement. The Analysis of Variance (ANOVA) was applied to analyze the test data. The analysis shows that all four factors are significant to the temperature measurements in the gasifier simulator (cold model). The regression analysis for the case with the normalized room temperature shows that linear model fits the temperature data with 82% accuracy (18% error). The regression analysis for the case without the normalized room temperature shows 72.5% accuracy (27.5% error). The nonlinear regression analysis indicates a better fit than that of the linear regression. The nonlinear regression model's accuracy is 88.7% (11.3% error) for normalized room temperature case, which is better than the linear regression analysis – 82%. Based the cold model testing and its analysis, it was found that normalized room temperature was a great help to analyze the experimental data in gasifier simulator (cold model) test.

The hot model thermocouple sleeve design and fabrication are completed. This special sleeve is designed to host the thermocouple. This sleeve can allow high-pressure purging gas to go through and blow the dirt off the thermocouple tip. The sleeve is made of a 1-inch stainless steel tube. Two flanges are welded to the sleeve. The one 2-inch away from the edge is used to connect to the flange of the gasifier simulator. The other flange at the edge is connected to thermocouple flange.

The gasifier simulator (hot model) design and the fabrication are completed in accordance to the proposed schedule. The gasifier simulator (hot model) body is made of carbon steel pipe of 24-inch high and 8-inch outer diameter. The thickness of the gasifier simulator (hot mode) is 0.25-inch.

The electric heating coil is installed inside the gasifier chamber. The heating element of the heating coil is L17-10C nichrome wire coil which can heat the inside material up to 1200 °C (2192 °F) with 3 KW of inputted electric power.

The refractory layer was attached to the inner side of the chamber wall to maintain relative high temperature which can simulate the real gasification environment. A certain amount of bars were welded to the wall to hold the refractory layer. The special boiler refractory cement was used as the refractory material of the gasifier simulator (hot model). The heat conduction coefficient of the refractory is $0.8 \text{ w/(m } ^\circ\text{C)}$.

The system tests of the gasifier simulator (hot model) were conducted and some modifications such as sealing enhancement, air injection port adjustment, and heating coil adjustment were made. Based on the system tests and results analysis, the gasifier simulator (hot model) met the proposed design requirements and is ready for systematic test.

The ultrasonic cleaning method is under evaluation and will be further studied for the gasifier simulator (hot model) application. The progress of this project has been on schedule.

3. EXPERIMENTAL

3.1. Gasifier Simulator (Cold Model) Systematic Test

As a continuation of the last semi-annual report, the gasifier simulator (cold model) testing parameters were set in the following settings. All together four (4) parameters are being tested at mixed levels shown in Table 1. Hence, thirty-two (32) cold model tests have been conducted.

Table 1. Test Parameters and the Level Design in the Gasifier simulator
(cold model) Simulation

Parameter 1
Irritation air flow rate:
Level 1: 0.0141 m ³ /s
Level 2: 0.0200 m ³ /s
Level 3: 0.0253 m ³ /s
Parameter 2
Compressed air injection frequency
Level 1: 1/120 hz
Level 2: 1/60 hz
Level 3: 1/30 hz
Parameter 3
Weight of the simulated dust
Level 1: 200 grams
Level 2: 400 grams
Parameter 4
Ultrasonic Application
Level 1: No
Level 2: 1 device
Level 3: 2 devices

The system tests results were reported in the last semi-annual report. The cold model met the design requirement and was ready for the systematic testing. The detailed experimental procedure is shown as follows. 1) Assemble the gasifier simulator (cold model), blower,

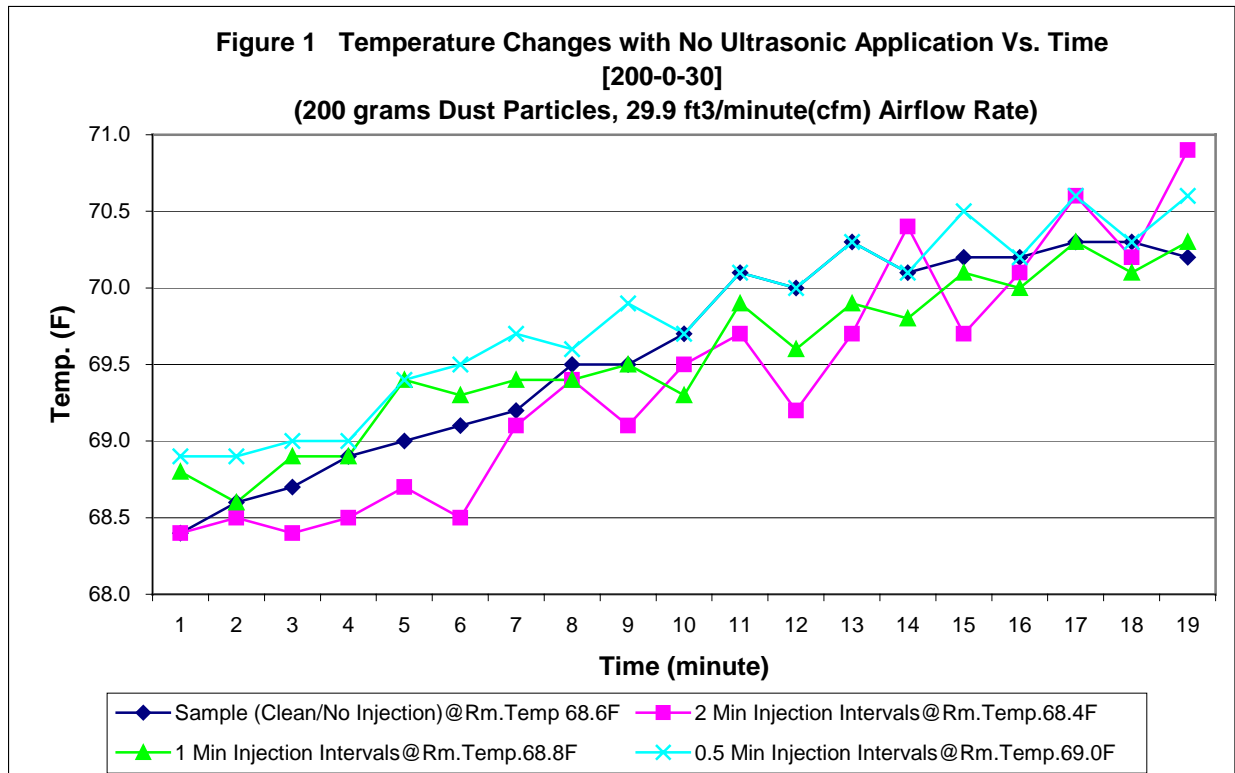
manometer, and filter together. 2) Put certain amount of filtered sawdust (dust particle; size distribution: 250 μm to 450 μm) on the distributor plate. 3) Calibration of the manometer and electronic scale. 4) Set the gasifier simulator (cold model) into different cases for testing. 5) Operate the voltage regulator to obtain the different experimental conditions. 6) Record the experimental temperature data.

The ultrasonic attachment used in the gasifier simulator (cold model) systematic test was a 40kHz transducer, which was driven by 120 volts electric power. The transducers were mounted on the sleeve. The transducer face was pointed to the thermocouple tip with 0.25-inch distance. The ultrasonic implementation for the gasifier simulator (cold model) systematic tests was an air application, which meant that the air would be the medium to transport the ultrasound. This approach was designed to see the feasibility of ultrasonic application for cleaning purposes.

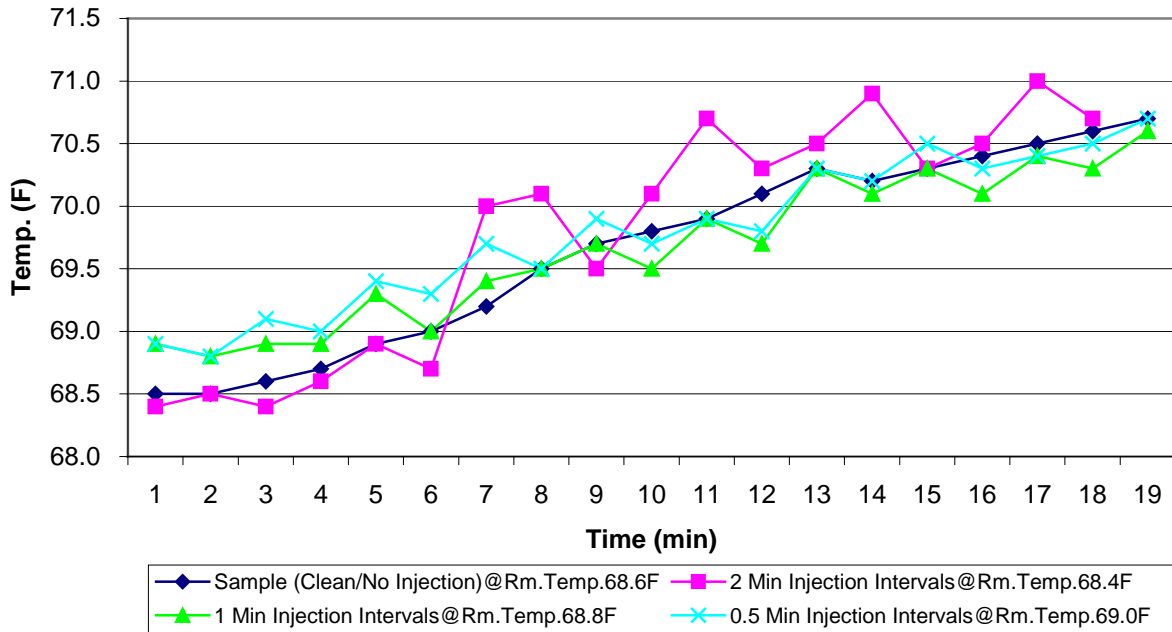
The detailed gasifier simulator (cold model) testing data are shown in Figures 1-24. Our previous system test revealed that the temperature readings at dirty dust environment differed from the sample curve at clean environment. Figures 1-9 show the temperature curves at the following experimental conditions- 200 grams of dust particles. Figures 1-3 show the temperature curve without ultrasonic application. The temperature reading at 1 min, 2 min, and 0.5 min injection intervals fluctuated over the sample temperature curve at the clean environment. This result indicated that the air injection did clean the thermocouple tip. From Figures 1-3, it can be seen that the airflow rate did not have the clear trend of changing fluctuations. Figures 4-6 show the temperature curve with one (1) ultrasonic application. Figures 4-6 show similar result of Figures 1-3. It is believed that one (1) ultrasonic air application does not have significant impact on the temperature readings. Figures 7-9 show the temperature curve with two (2) ultrasonic applications. Figures 7-9 indicate that two (2) ultrasonic air applications may not have

significant impact on the temperature readings. Figures 10-14 show the repeatability of the tests. Overall temperature curves matched each other pretty well. This indicates the repeatability of the gasifier simulator (cold model) systematic tests. Figures 16-24 show the temperature curves at the following experimental conditions- 400 grams of dust particles. All the curves seem similar to the curves in Figures 1-9. Among Figures 16-24, Figures 16-18 show the temperature curve with no ultrasonic application. Figures 19-21 show the temperature curve with one (1) ultrasonic application. Figures 22-24 show the temperature curve with two (2) ultrasonic applications.

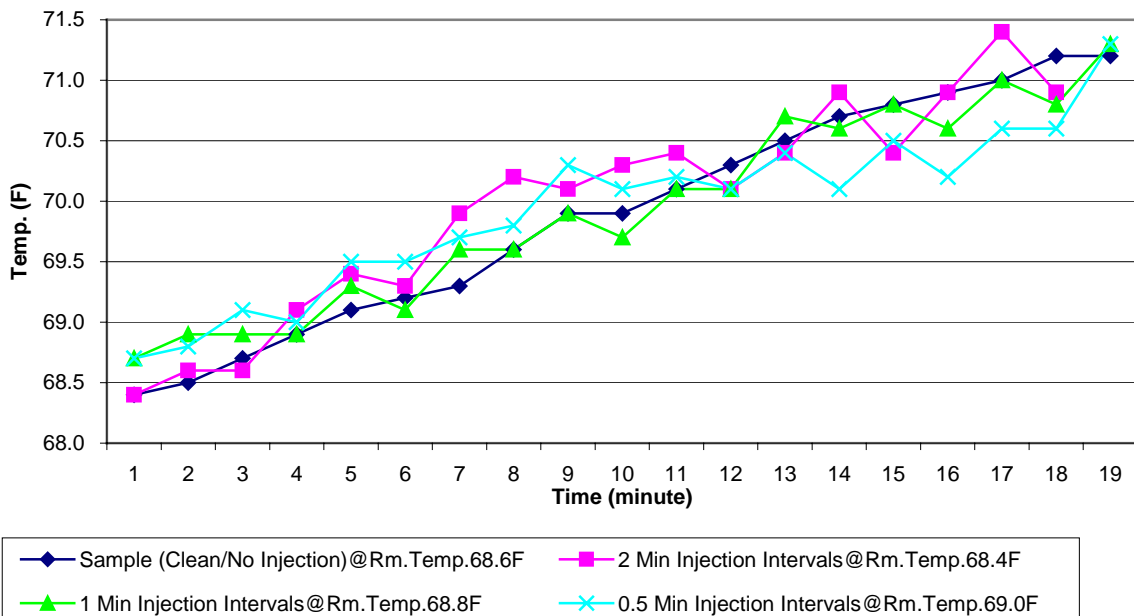
From Figures 1-24, it can be seen that the air injection cleaning method did have positive impact to bring the differed temperature back to the clean sample. By comparing the curves, one (1) minute injection interval had the best performance for the accurate temperature measurement. The result also indicates that the dust amount in the gasifier simulator (hot model) did not affect the temperature.

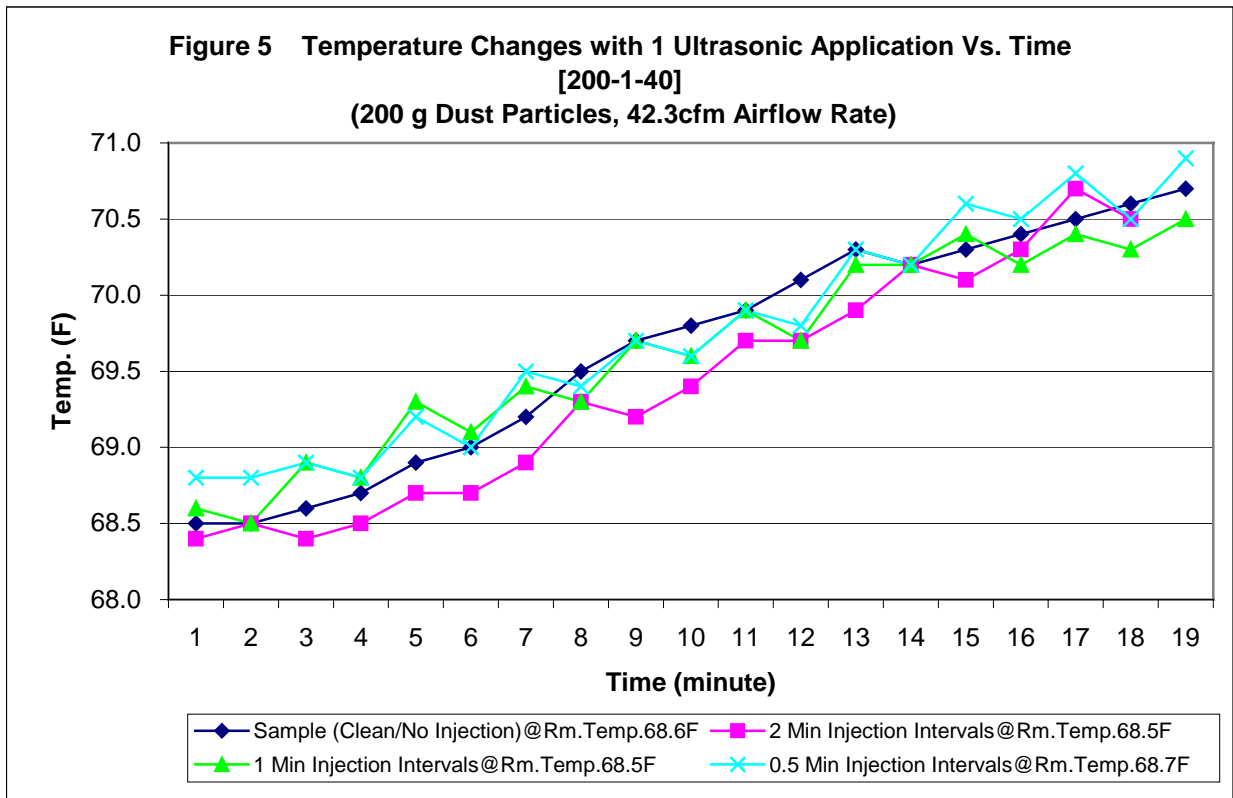
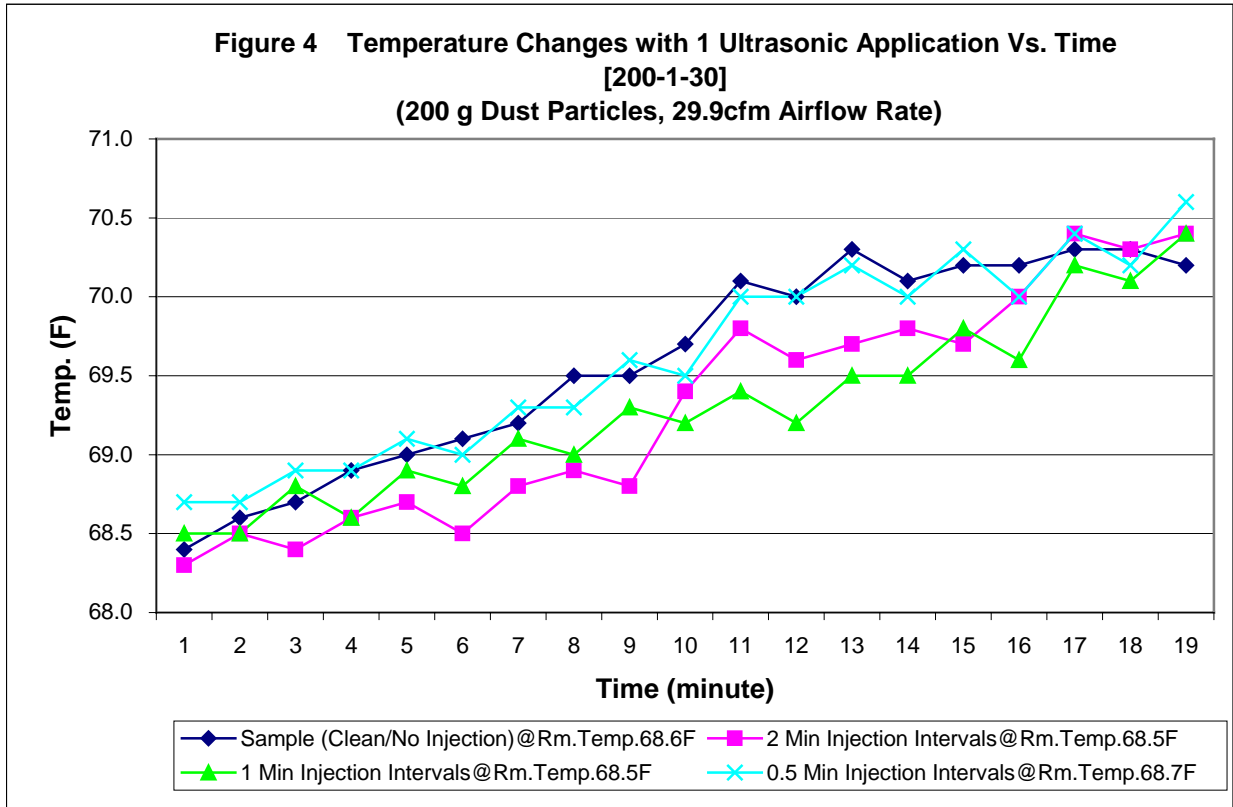


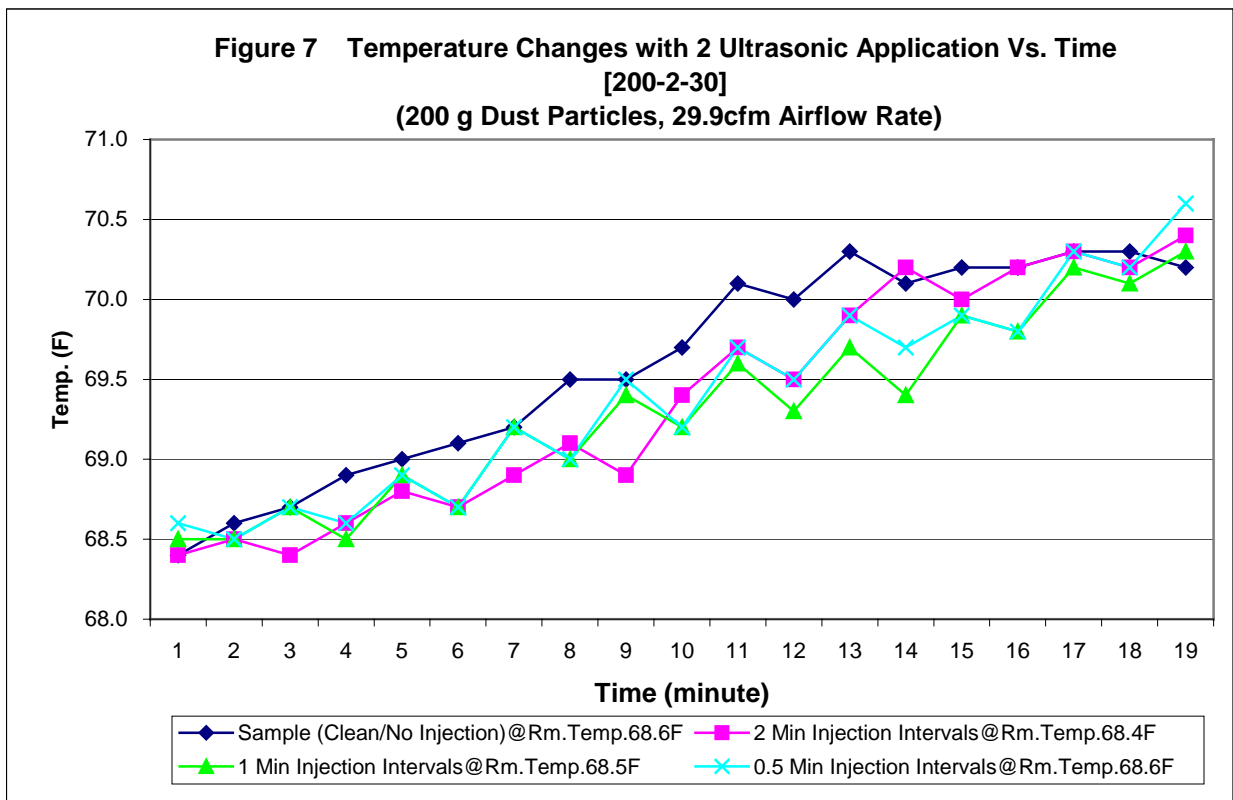
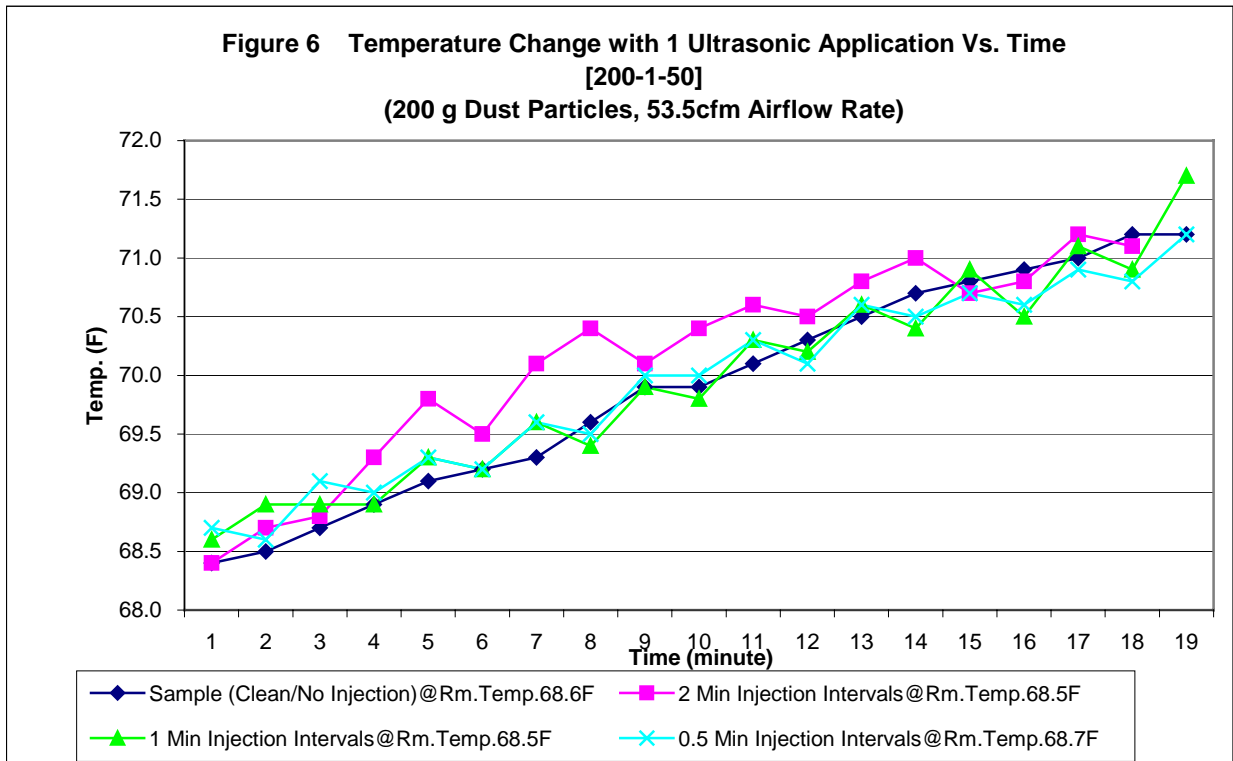
**Figure 2 Temperature Changes with No Ultrasonic Application Vs. Time
[200-0-40]
(200 g Dust Particles, 42.3cfm Airflow Rate)**

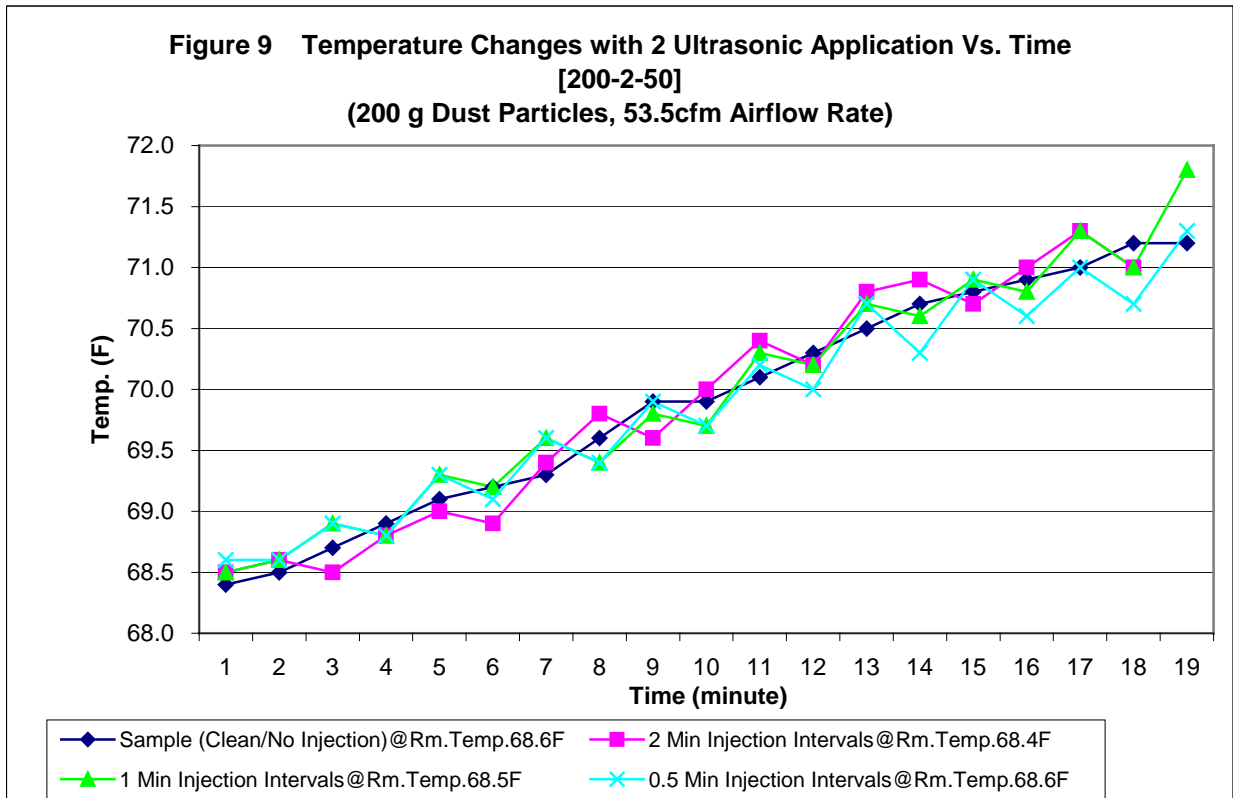
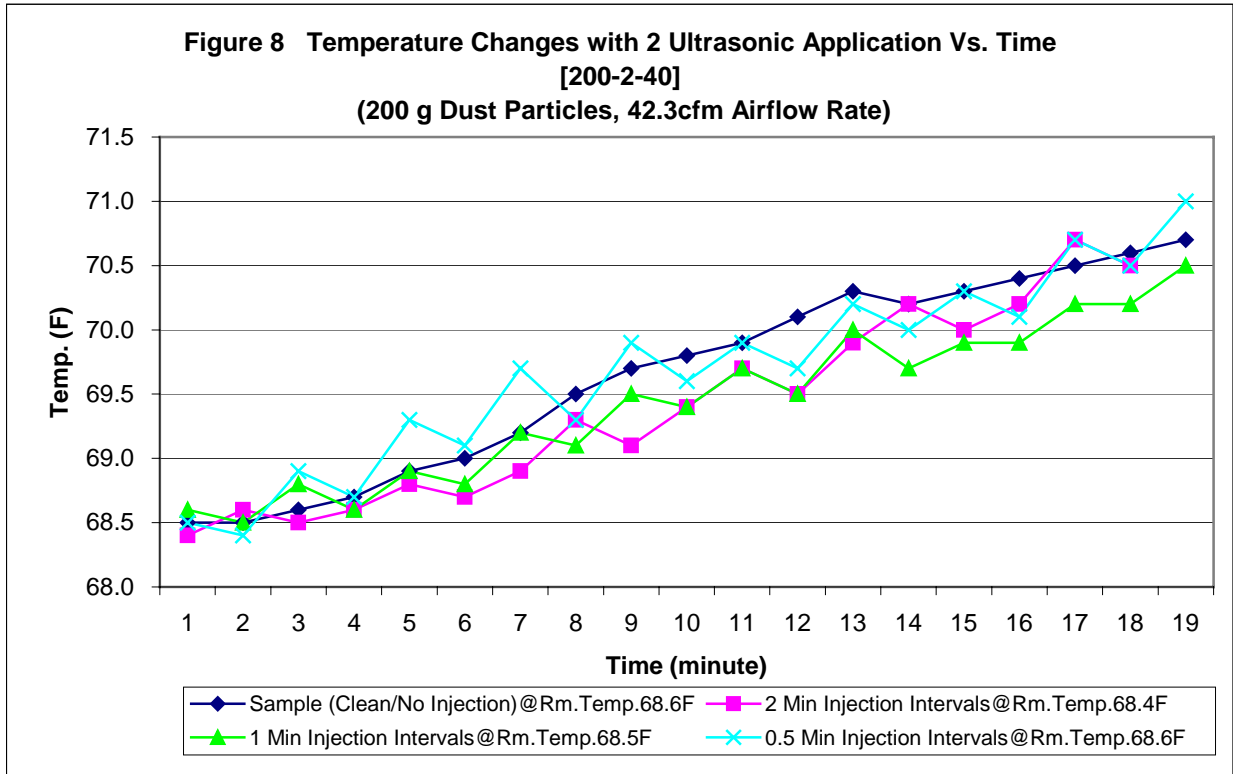


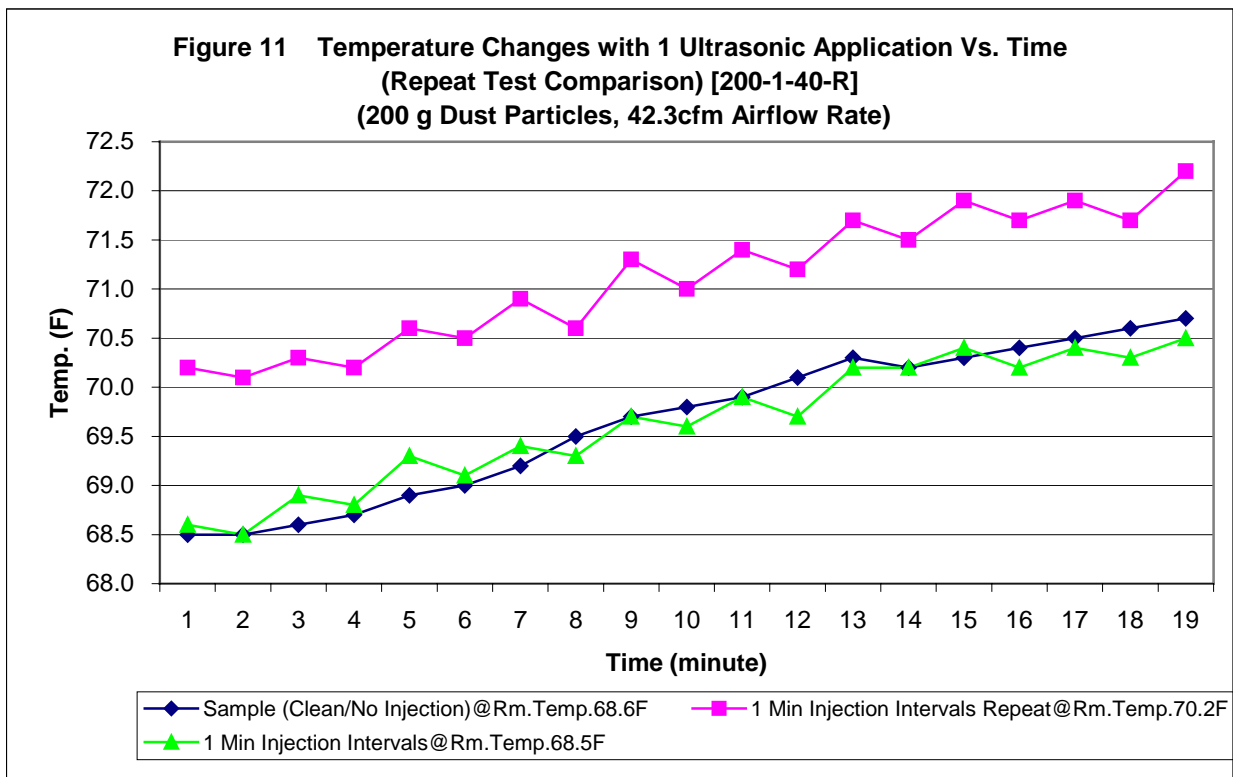
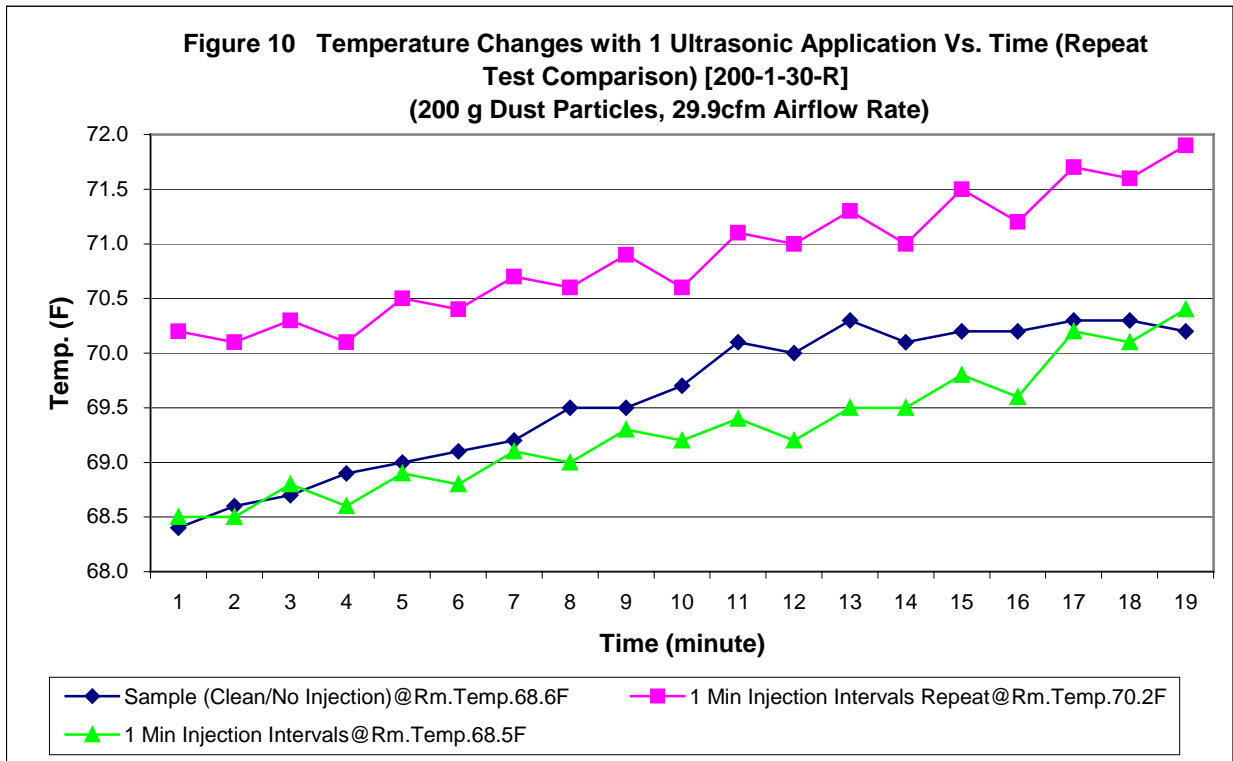
**Figure 3 Temperature Changes with No Ultrasonic Application Vs. Time
[200-0-50]
(200 g Dust Particles, 53.5cfm Airflow Rate)**



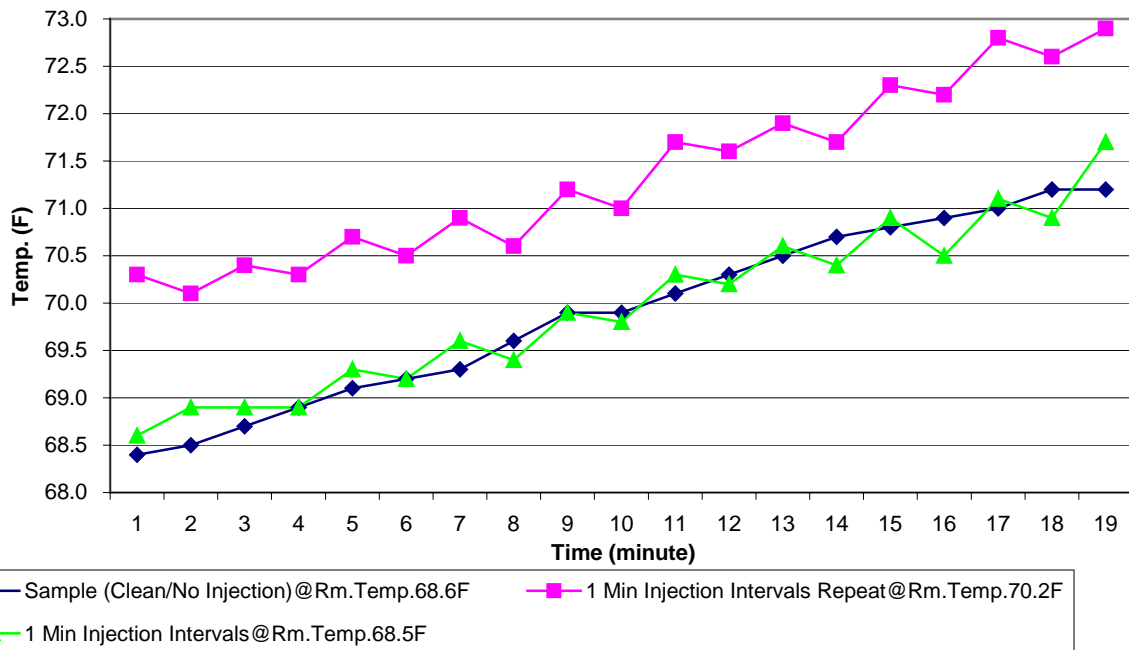




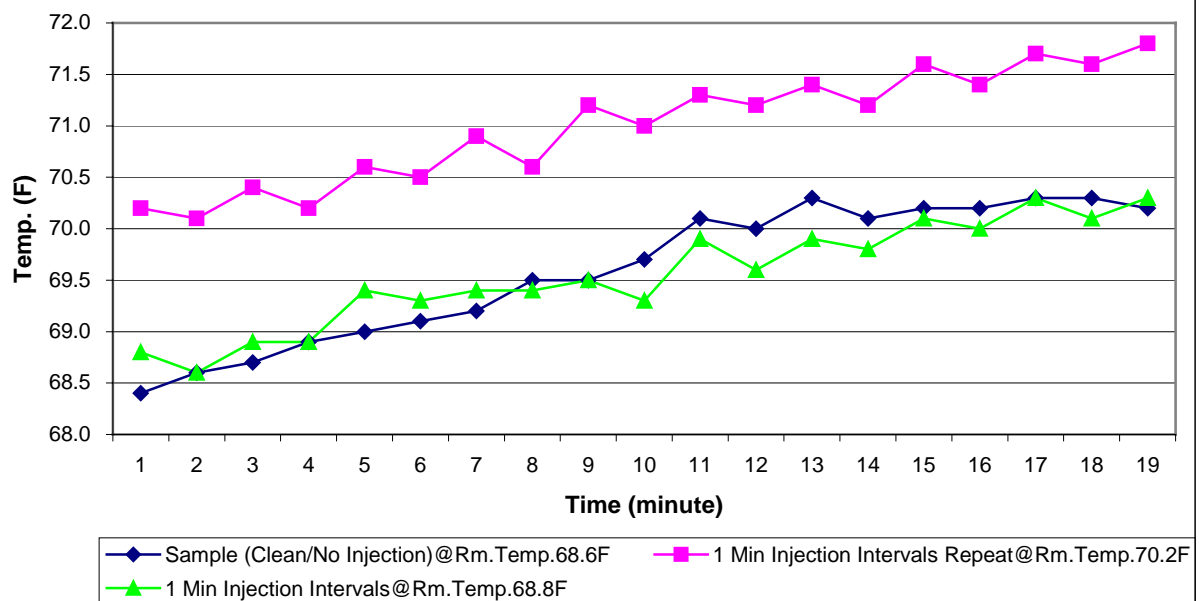




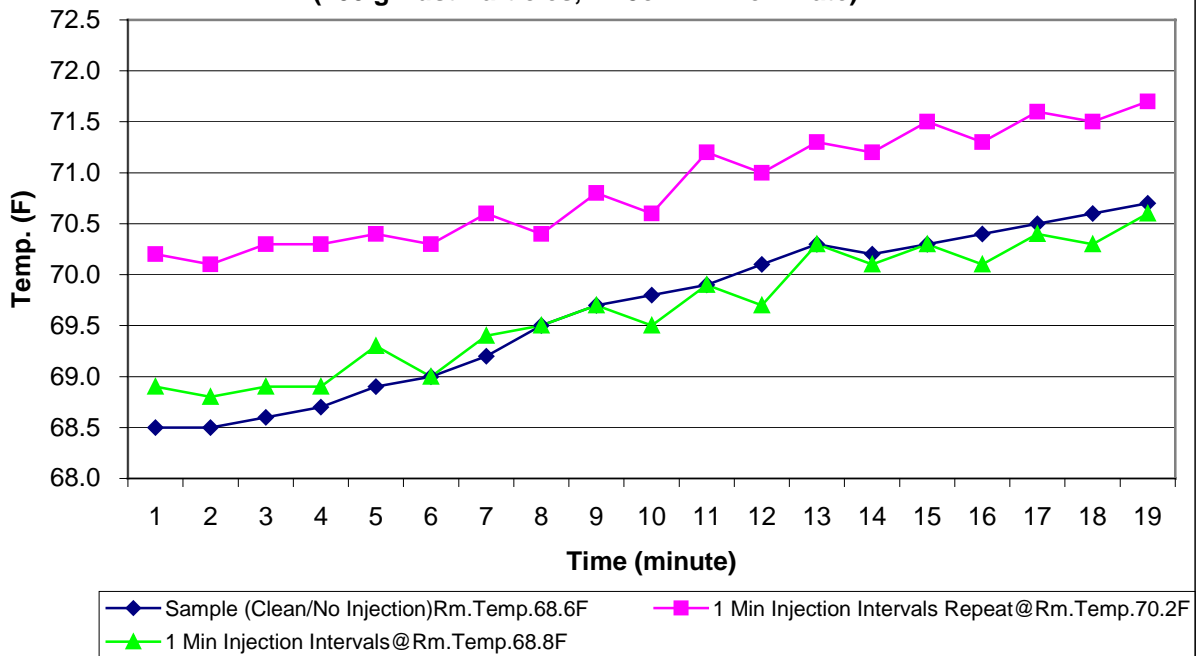
**Figure 12 Temperature Changes with 1 Ultrasonic Application Vs. Time
(Repeat Test Comparison) [200-1-50-R]
(200 g Dust Particles, 53.5cfm Airflow Rate)**



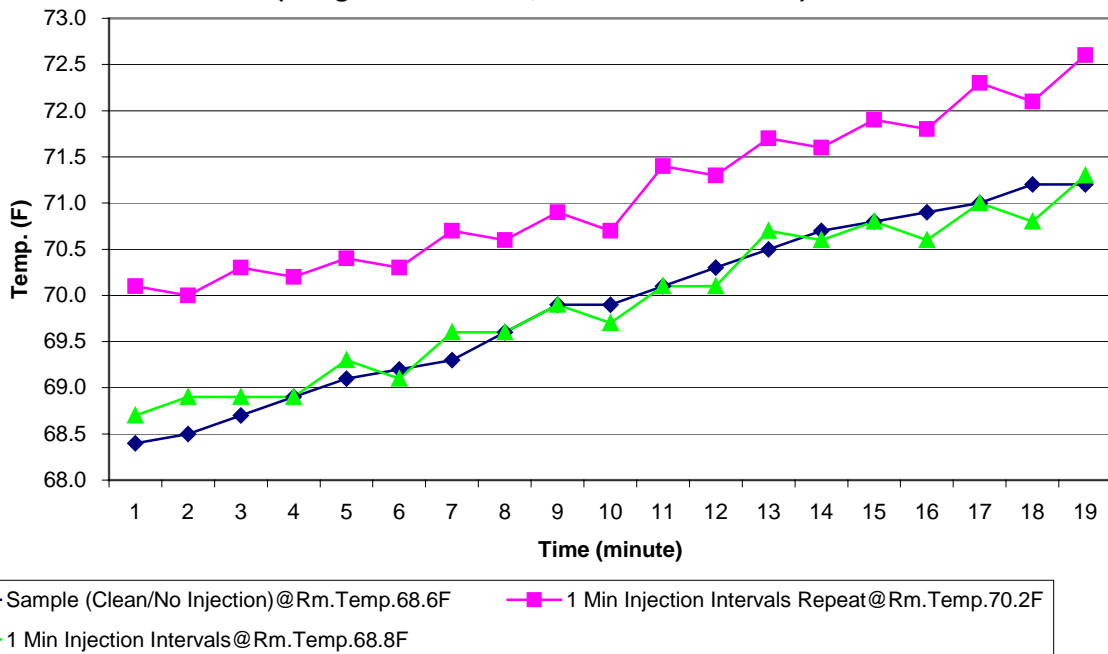
**Figure 13 Temperature Changes with 0 Ultrasonic Application Vs. Time
(Repeat Test Comparison) [200-0-30-R]
(200 g Dust Particles, 29.9cfm Airflow Rate)**



**Figure 14 Temperature Changes with 0 Ultrasonic Application Vs. Time
(Repeat Test Comparison) [200-0-40-R]
(200 g Dust Particles, 42.3cfm Airflow Rate)**



**Figure 15 Temperature Changes with 0 Ultrasonic Application Vs. Time
(Repeat Test Comparison) [200-0-50-R]
(200 g Dust Particles, 53.5cfm Airflow Rate)**



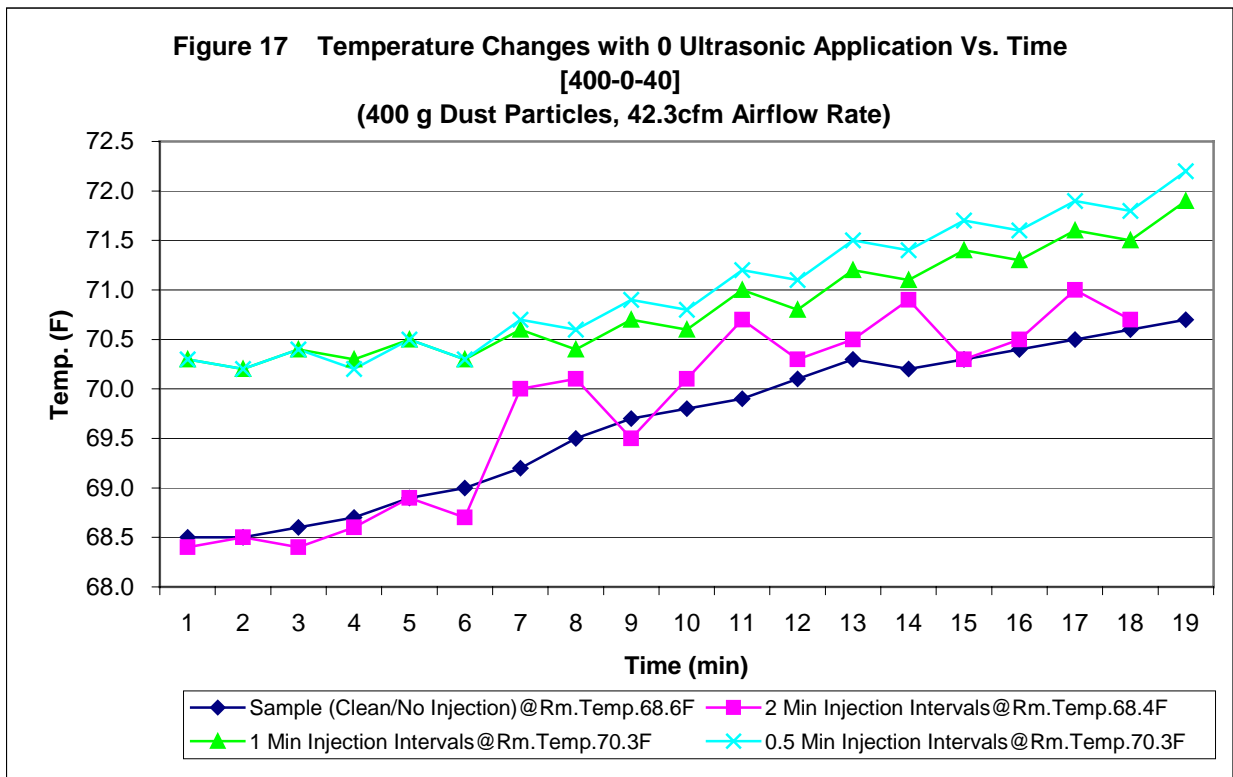
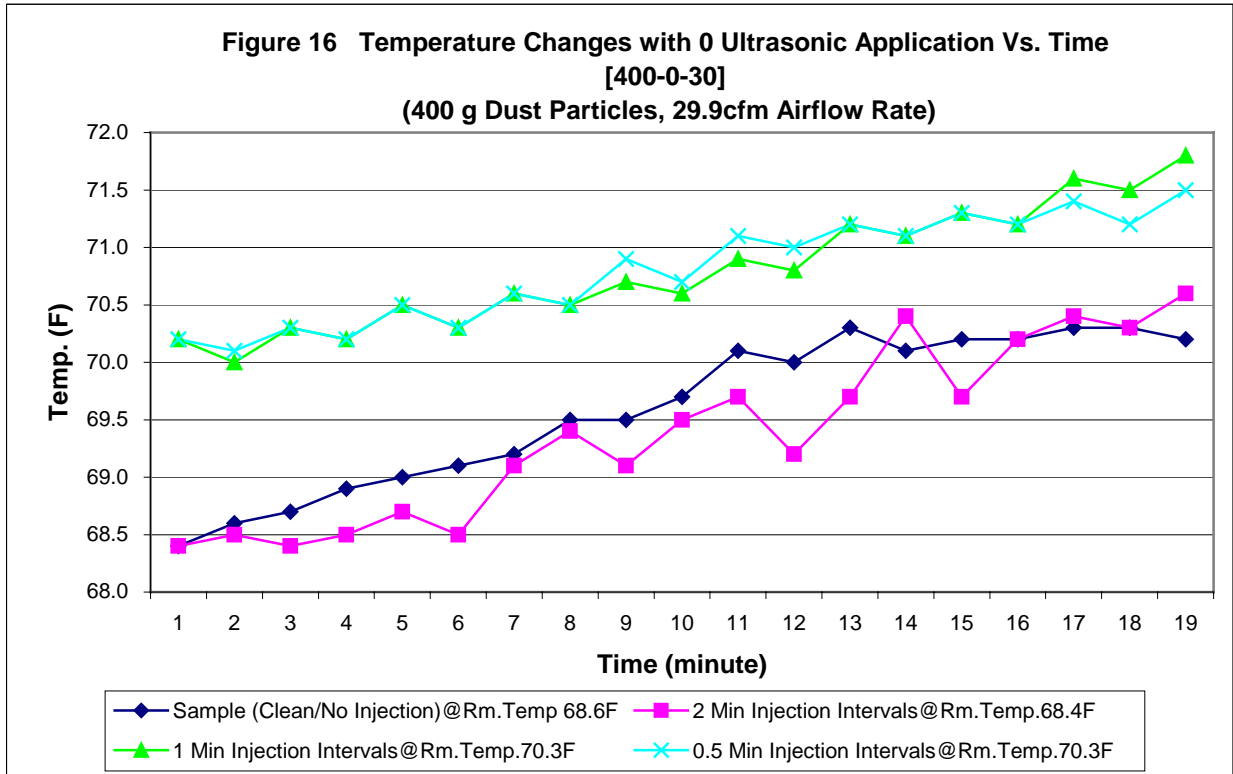


Figure 18 Temperature Changes with 0 Ultrasonic Application Vs. Time
[400-0-50]
(400 g Dust Particles, 53.5cfm Airflow Rate)

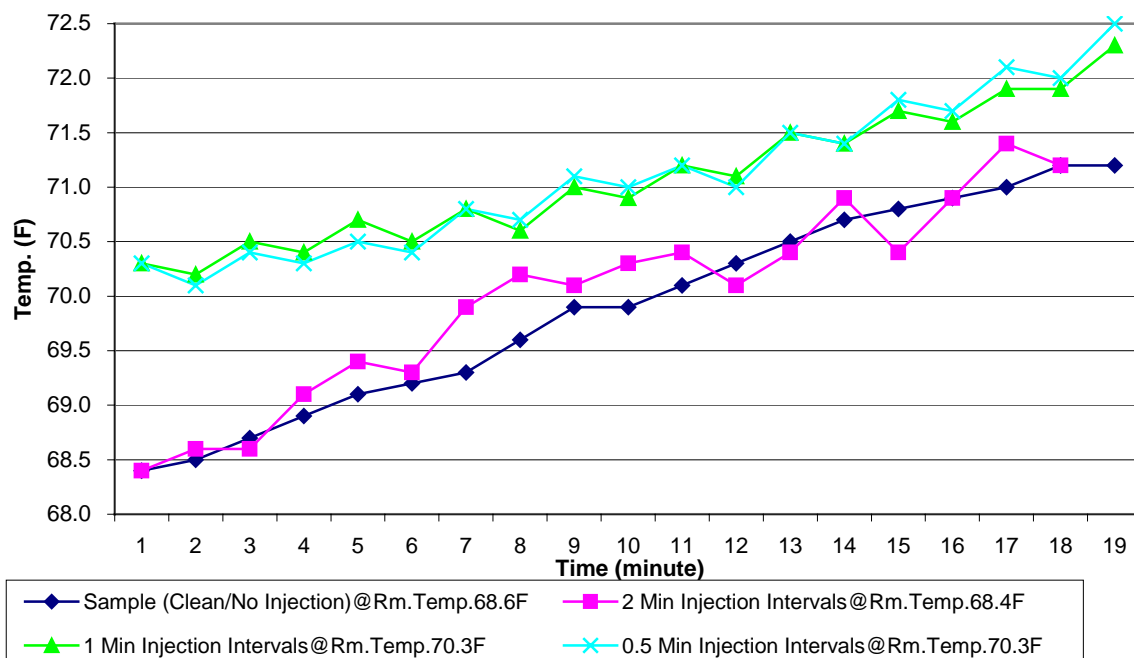


Figure 19 Temperature Changes with 1 Ultrasonic Application Vs. Time
[400-1-30]
(400 g Dust Particles, 29.9cfm Airflow Rate)

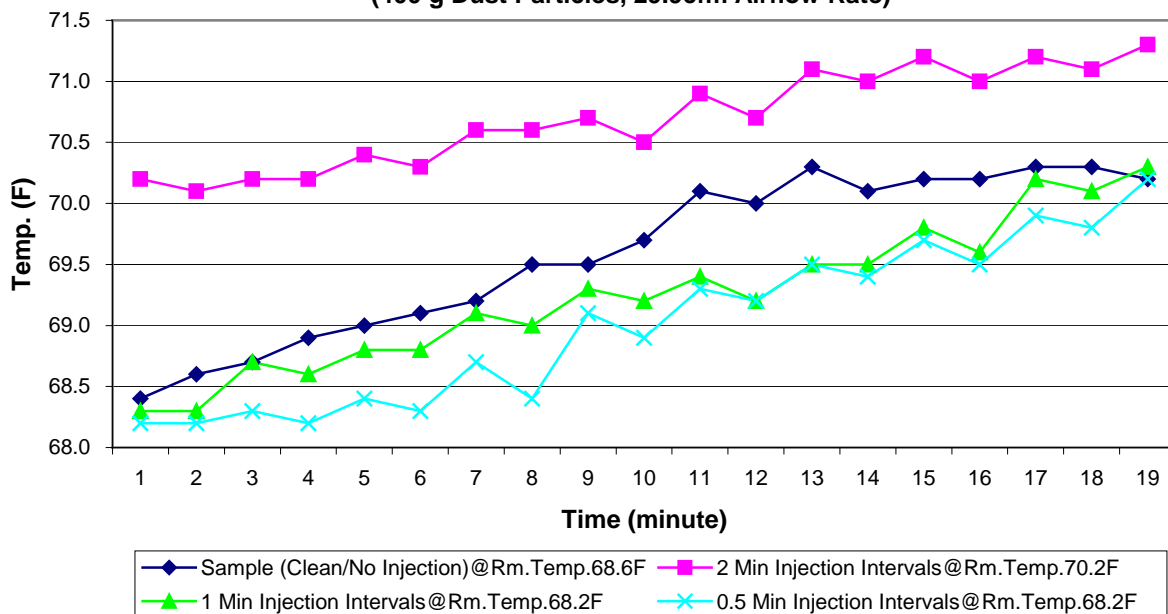


Figure 20 Temperature Changes with 1 Ultrasonic Application Vs. Time
[400-1-40]
(400 g Dust Particles, 42.3cfm Airflow Rate)

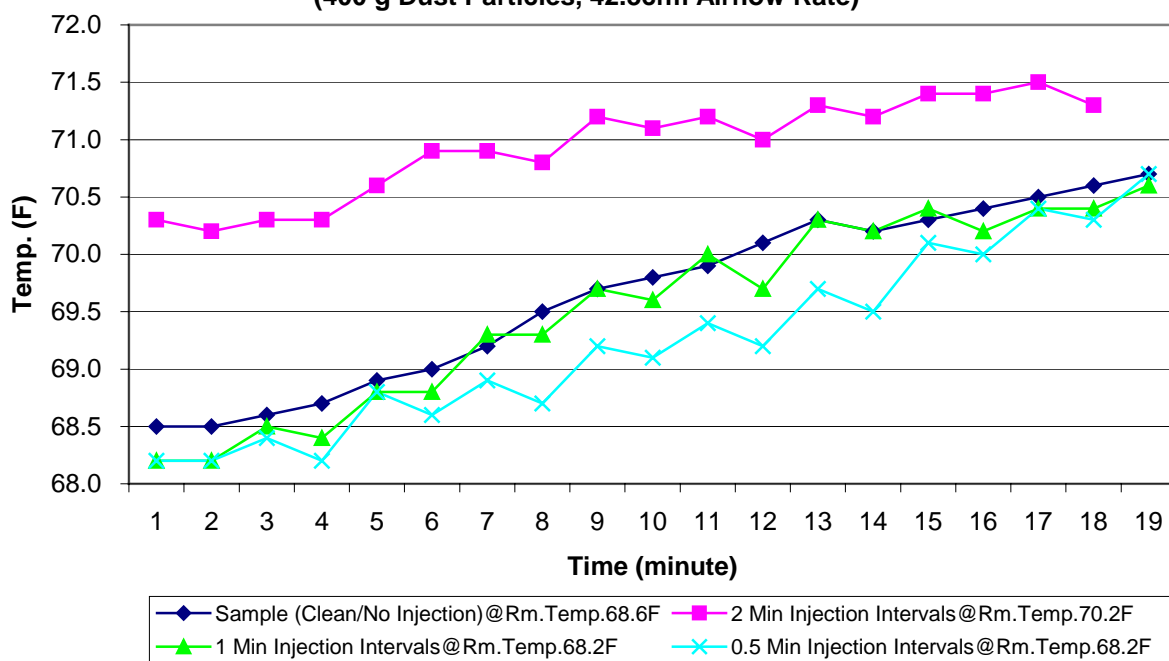
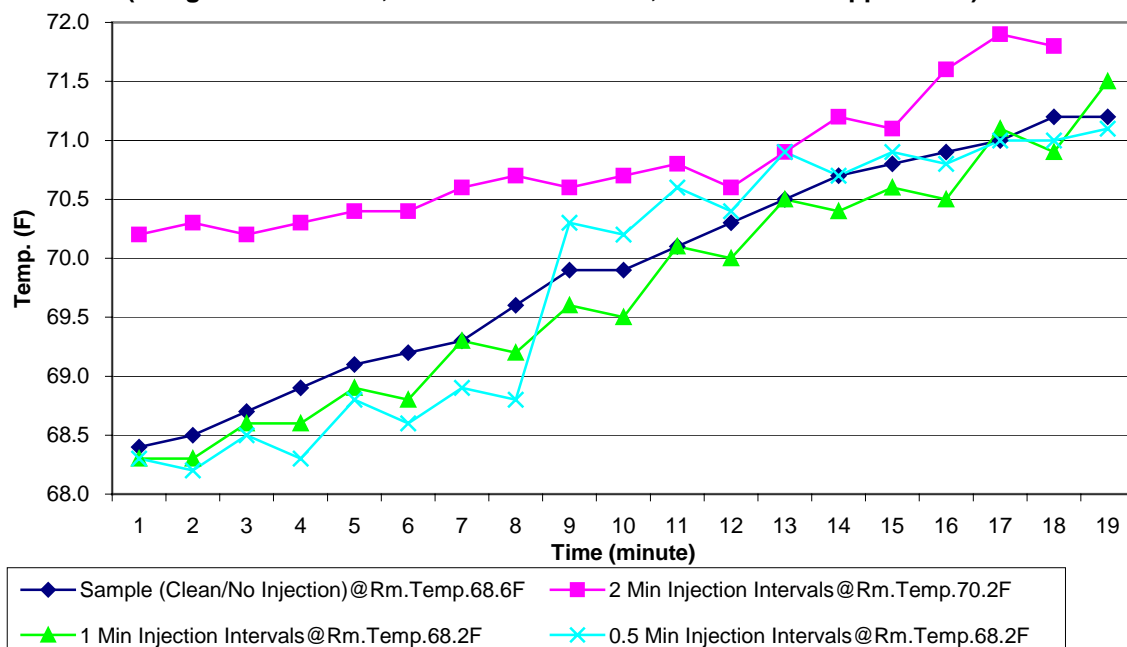
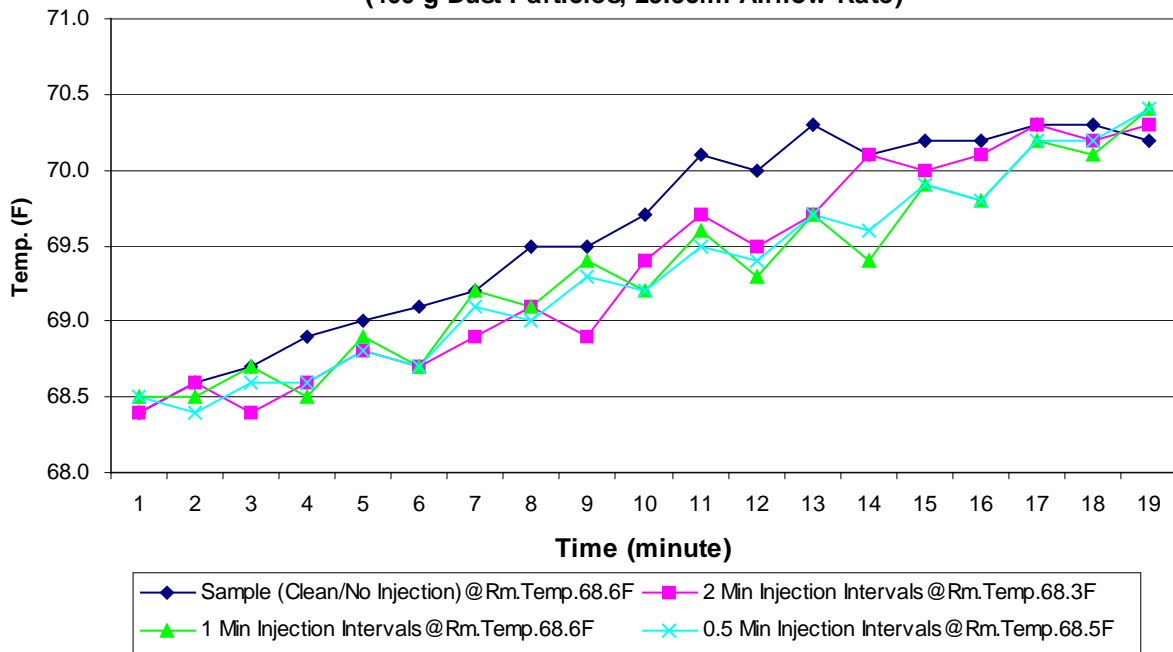


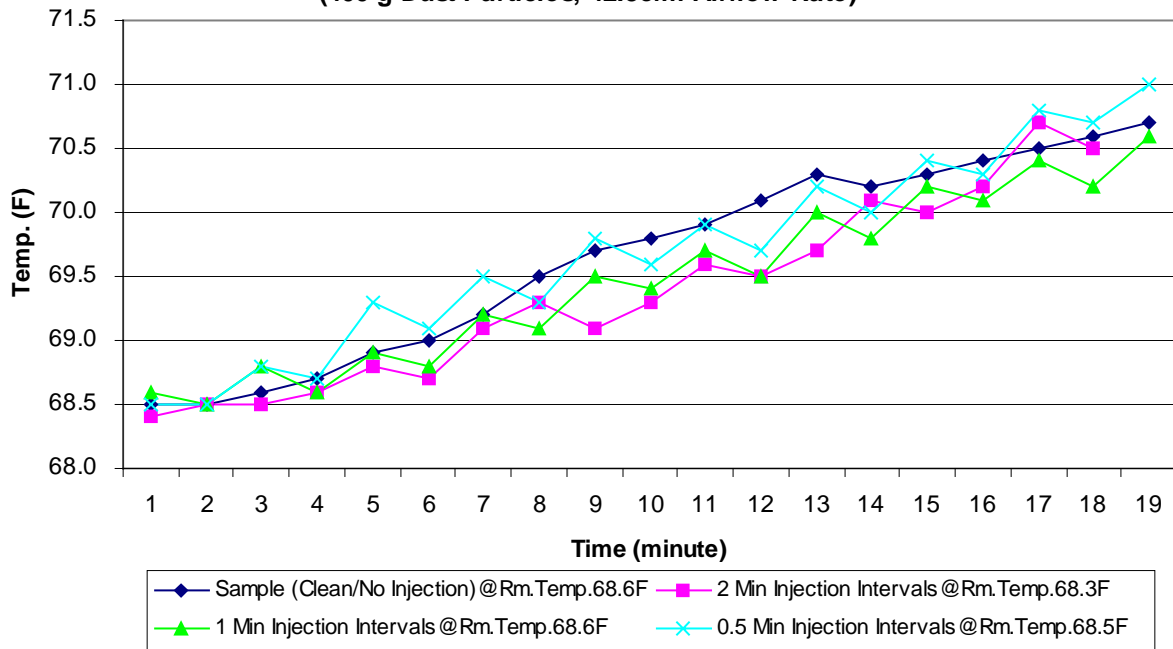
Figure 21 Temperature Changes with 1 Ultrasonic Application Vs. Time
[400-1-50]
(400 g Dust Particles, 53.5cfm Airflow Rate, 1 Ultrasound Application)

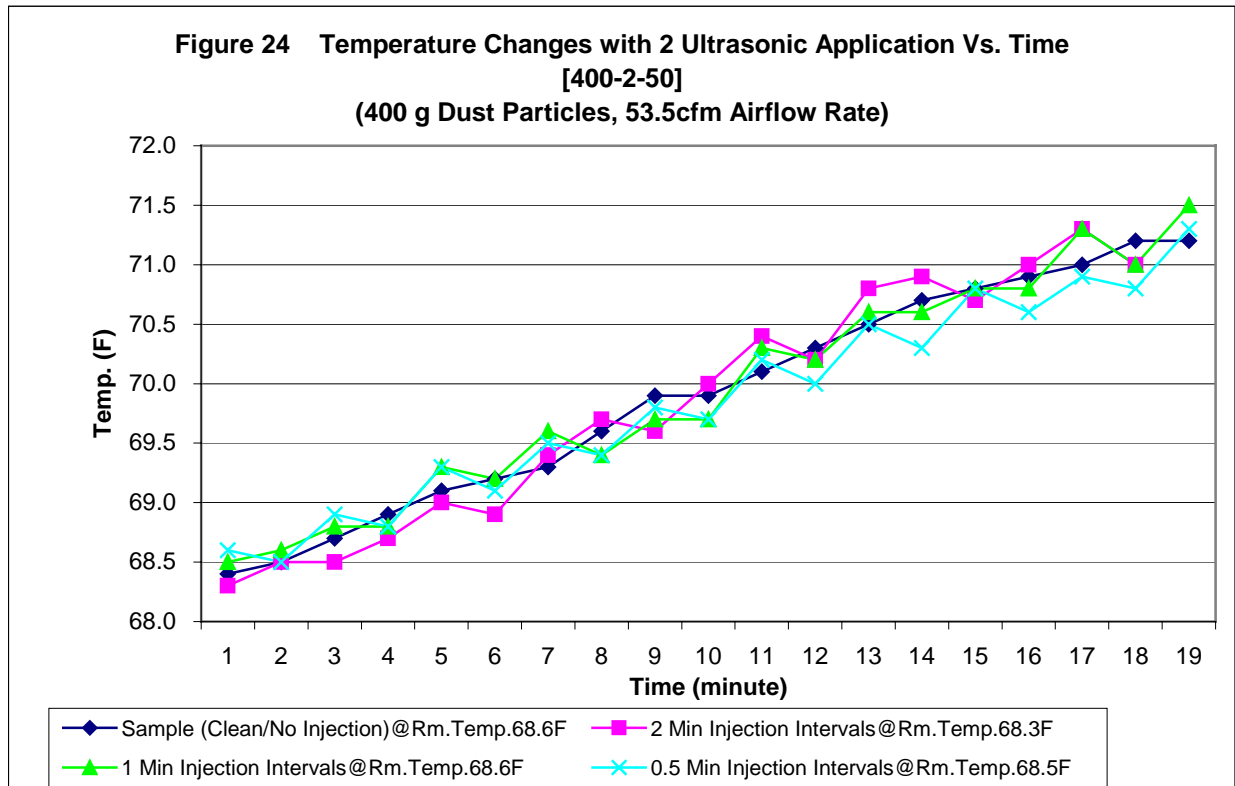


**Figure 22 Temperature Changes with 2 Ultrasonic Application Vs. Time
[400-2-30]
(400 g Dust Particles, 29.9cfm Airflow Rate)**



**Figure 23 Temperature Changes with 2 Ultrasonic Application Vs. Time
[400-2-40]
(400 g Dust Particles, 42.3cfm Airflow Rate)**





The schematic diagram of the gasifier simulator (cold model) testing facility is shown in Figure 25.

3.2. Gasifier Simulator (Hot Model) System Test

The system tests were conducted to determine the maximum temperature which the gasifier simulator (hot model) can reach. The maximum temperature of the gasifier simulator (hot model) could reach 1200 C, which suffices the design requirement. The system needed 50 minutes warm up time to reach the maximum temperature, and 180 minutes to cool down to the ambient temperature. The heating up and cooling down curves are shown in Figures 26 and 27. At first 10 minutes of the start up period, the temperature went up sharply. After this period, the temperature went up gradually with a deceased slope. The cooling down curve has the opposite

behavior to the start-up period. At first 10-15 minutes, the temperature dropped sharply. After this time period, the temperature dropped with an increased slope.

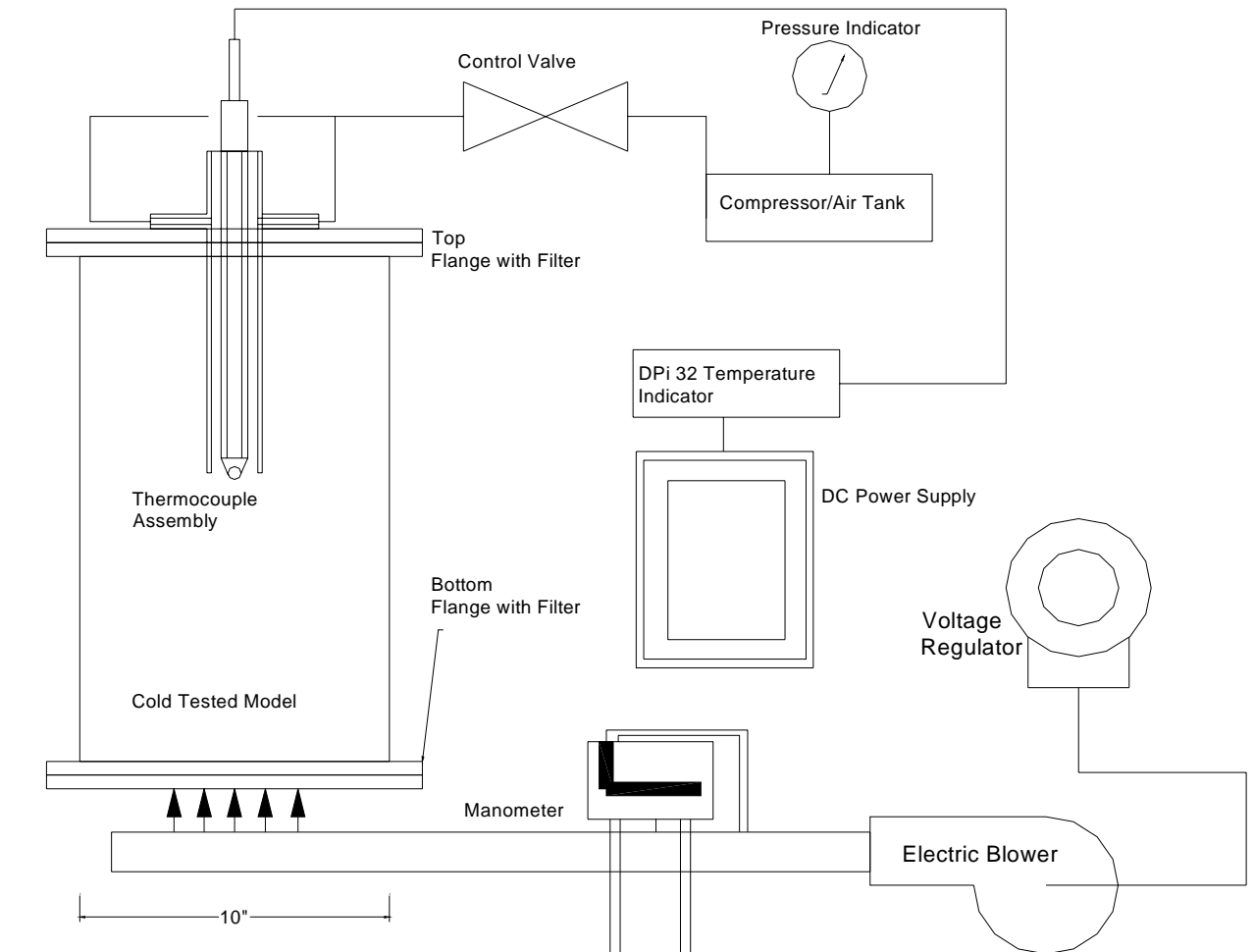
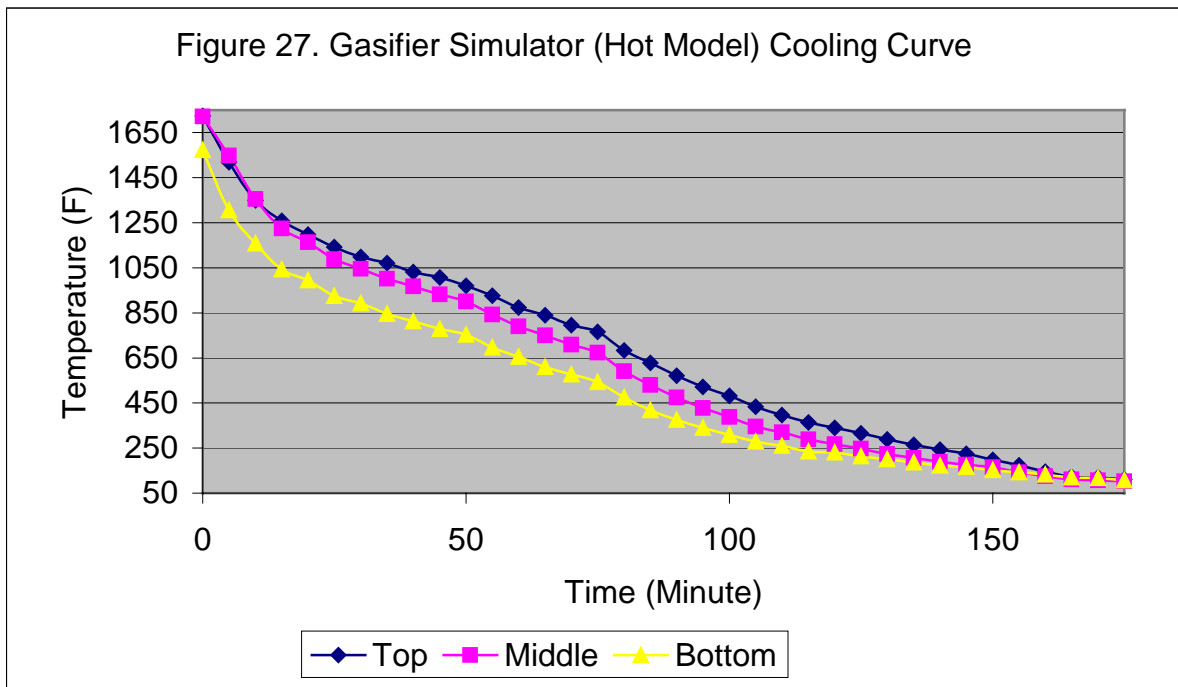
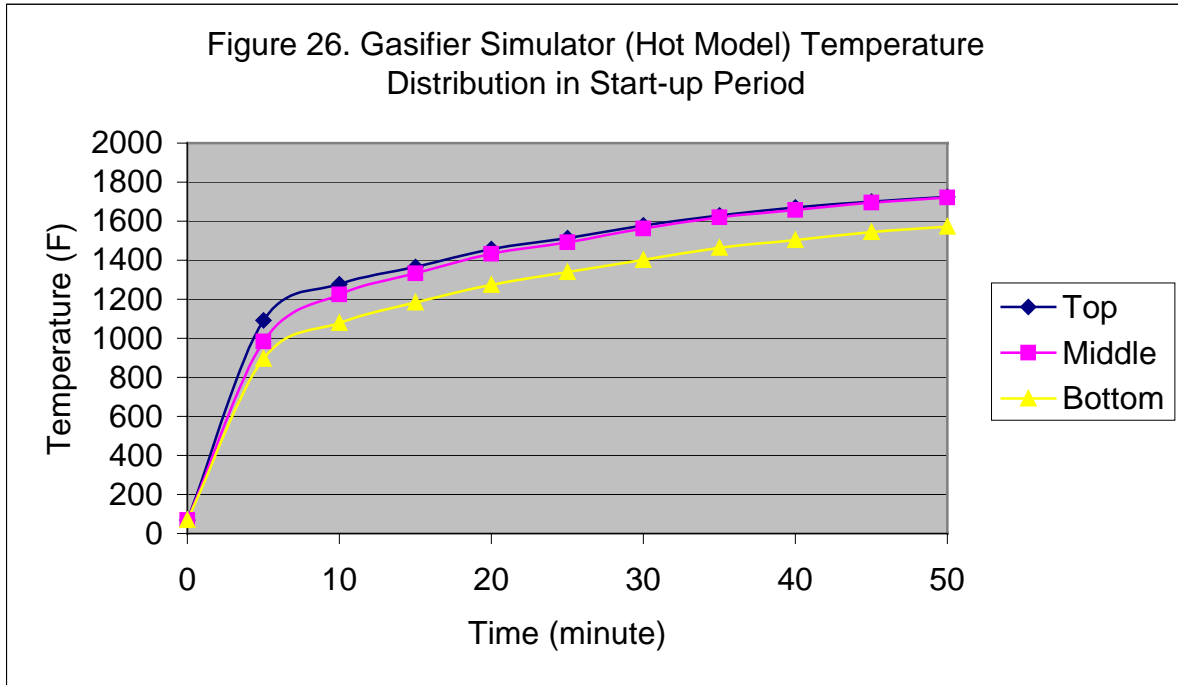


Figure 25. The Gasifier Simulator (Cold Model) Testing Facility with the Thermocouple Assembly



During the gasifier simulator (hot model) system tests, several problems occurred. The gasifier simulator (hot model) sealing performance was critical. The high temperature sealing cement was used to stop the hot gas from leaking from the top electric cable channel. The high

temperature resistant gaskets were used on all flange connections. The leaking could be controlled to the minimum level for the systematic test.

4. RESULTS AND DISCUSSION

4.1. Data Analysis and Modeling on Gasifier Simulator (Cold Model) Testing

4.1.1 ANOVA/Regression Analysis on Gasifier Simulator (Cold Model) Testing

Due to the heat generated by the electric motor, the temperature increased with the time. This temperature increment was used to evaluate the impacts of the experimental parameters. The temperature measurement data in the gasifier simulator (cold model) testing are shown in the Appendix A.

All the data were inputted to the Minitab for analysis. Basically, for the Analysis of Variances (ANOVA), five (5) factors were considered as the significant factors that can affect the temperature reading in the gasifier simulator (cold model). These five (5) factors are time(t), dust particle amount (DP_{amount}), number of ultrasonic applications (N_{ultra}), air flow rate (F_{air}), and injection time intervals ($It_{\text{intervals}}$). DP_{amount} , N_{ultra} , F_{air} , and $It_{\text{intervals}}$ levels design are listed in the above Table 1. The level design of the time is shown below.

Time (t): Nineteen (19) levels

Level 1: 1 min; Level 2: 2 min; Level 3: 3 min; Level 4: 4 min; Level 5: 5 min; Level 6: 6 min

Level 7: 7 min; Level 8: 8 min; Level 9: 9 min; Level 10: 10 min; Level 11: 11 min;

Level 12: 12 min; Level 13: 13 min; Level 14: 14 min; Level 15: 15 min; Level 16: 16 min;

Level 17: 17 min; Level 18: 18 min; Level 19: 19 min

ANOVA Analysis:

The analysis was conducted on two cases, without normalized room temperature and with normalized room temperature.

Case 1: Without Normalized Room Temperature

One-way Analysis of Variance was conducted on all five (5) parameters respectively. The results showed that all five (5) factors have significant impact on the temperature reading in the gasifiers. Among these factors, time (t) has the most significant impact on the temperature reading. The ultrasonic application has the second significant the impact on the temperature reading. Air flow rate has the third significant impact on the temperature reading. The dust particle weight has the fourth significant impact on the temperature reading. The injection time interval has the least significant impact on the temperature reading.

The general linear model analysis was also conducted to determine if any correlation among the factors. No obvious coloration was found since the results for each factor are similar to the one-way ANOVA.

Case 2: With Normalized Room Temperature

Similar results were found in the ANOVA with normalized room temperature. All five (5) factors were found all significant for the temperature reading. The sequence was also similar to the ANOVA without the normalized room temperature.

4.1.2. Linear Regression Analysis on Gasifier Simulator (Cold Model) Testing

The regression analysis was conducted on two cases, without the normalized room temperature and with the normalized room temperature.

Case 1: With Normalized Room Temperature

The regression equation for the temperature reading in the gasifier simulator (cold model) under normalized room temperature is shown in equation (1).

$$\text{Temp. Readings} = 67.2 + 0.126 * (\text{Time}) + 0.0746 * (\text{Ultrasonic}) + 0.128 * (\text{Injection Intervals}) + 0.0213 * (\text{Airflow Rate}) - 0.000366 * (\text{Dust Particles}) \quad (1)$$

The statistical results of the linear regression process with normalized room temperature are shown in Table 2.

Table 2. Statistical Output of the Linear Regression Process with Normalized Room Temperature

Predictor	Coef	StDev	T	P
Constant	67.1847	0.0636	1055.58	0.000
Time	0.125692	0.001904	66.00	0.000
Ultrasou	0.07456	0.01278	5.84	0.000
Injectio	0.12807	0.01673	7.66	0.000
Airflow	0.021295	0.001082	19.68	0.000
Dust Par	-0.0003665	0.0001043	-3.51	0.000
S = 0.3341 R-Sq = 82.6% R-Sq(adj) = 82.5%				

As the results show, the accuracy of this linear model is 82.5%, which is equivalent to 17.5% error. This accuracy is derived based on the Mean Square Error (MSE) analysis.

Case 2: Without the Normalized Room Temperature

The regression equation for the temperature reading in the gasifier simulator (cold model) under normalized room temperature is shown below as equation (2).

$$\text{Temp. Readings} = 67.5 + 0.126 * (\text{Time}) - 0.283 * (\text{Ultrasonic}) + 0.0070 * (\text{Injection Intervals}) + 0.0213 * (\text{Airflow Rate}) + 0.00164 * (\text{Dust Particles}) \quad (2)$$

The statistical results of the linear regression process without normalized room temperature are shown in Table 3.

Table 3. Statistical Output of the Linear Regression Process without Normalized Room Temperature

Predictor	Coef	StDev	T	P
Constant	67.4847	0.0912	739.64	0.000
Time	0.125653	0.002730	46.03	0.000
Ultrasou	-0.28348	0.01831	-15.48	0.000
Injectio	0.00698	0.02398	0.29	0.771
Airflow	0.021271	0.001551	13.71	0.000
Dust Par	0.0016355	0.0001495	10.94	0.000
S = 0.4790 R-Sq = 72.3% R-Sq(adj) = 72.2%				

As the results show, the accuracy of this linear model is 72.5%, which is equivalent to 27.5% error. This accuracy is derived based on the Mean Square Error (MSE) analysis. The lower accuracy is believed to be caused by the un-normalized room temperature.

4.1.3. Non-Linear Regression Analysis on Gasifier Simulator (Cold Model) Testing Under Normalized Room Temperature Condition

As shown in the above linear regression analysis, it can be seen that linear relation is a great fit to the gasifier simulator (cold model) data under normalized room temperature. The non-linear regression analysis was still conducted to achieve more accuracy.

By study the data file, it can be found that most temperature fluctuate along a linear line. Hence, a SIN triangle function of the injection interval time was considered to add to the regression equation as shown in the equation (3). Since the good fit of the linear regression, the other factors remained linear form.

$$\text{Temp} = C0 + C1 * \text{time} + C2 * \text{ultras} + C3 * \text{SIN}(1.2 * \text{injint} + 0.89) + C4 * \text{afr} + C5 * \text{dpw} \quad (3)$$

The Run stopped after 4 model evaluations and 2 derivative evaluations. Iterations have been stopped because the relative reduction between successive residual sums of squares is at most $\text{SSCON} = 1.000\text{E-}08$.

From the above analysis, the coefficients C0, C1, C2, C3, C4, and C5 were determined, hence the equation (3) can be written as follows shown in Equation 4.

$$\text{Temp} = 67.4263882 + 0.125692001 * \text{time} + 0.074561327 * \text{ultras} - 0.16117338 * \text{SIN} (1.2 * \text{injint} + 0.89) + 0.021295344 * \text{afr} + -0.00036647 * \text{dpw} \quad (4)$$

The equation (4) shows the non-linear regression for the temperature reading in the gasifier simulator (cold model). The accuracy is 88.7% (equivalent to 11.3% error), which is better than the linear regression analysis.

4.2 Data Analysis on Gasifier Simulator (Hot Model) Testing

The data obtained from the hot model system test is being analyzed, similar analytical methods such as experimental design, regression, and ANOVA are being used as tools to reveal the temperature curve in the system test.

Table 4. Statistical Output of the Nonlinear Regression Process without Normalized Room Temperature

Source	DF	Sum of Squares	Mean Square
Regression	6	4948958.35093	824826.39182
Residual	1020	113.42907	.11120
Uncorrected Total	1026	4949071.78000	
(Corrected Total)	1025	655.10070	
R squared = 1 - Residual SS / Corrected SS = .88685			

Asymptotic 95 %				
Parameter	Estimate	Std. Error	Confidence Interval Lower	Confidence Interval Upper
C0	67.426388162	.061574158	67.3055616	67.547214666
C1	.125692001	.001900762	.121962150	.129421852
C2	.074561327	.012750667	.049540789	.099581865
C3	-.161173382	.020334909	-.201076421	-.121270343
C4	.021295344	.001080104	.019175864	.023414825
C5	-.000366472	.000104111	-.000570767	-.000162176

Asymptotic Correlation Matrix of the Parameter Estimates						
	C0	C1	C2	C3	C4	C5
C0	1.0000	-.3087	-.2071	-.1890	-.7350	-.5072
C1	-.3087	1.0000	.0000	.0000	.0000	.0000
C2	-.2071	.0000	1.0000	.0000	.0000	.0000
C3	-.1890	.0000	.0000	1.0000	.0000	.0000
C4	-.7350	.0000	.0000	.0000	1.0000	.0000
C5	-.5072	.0000	.0000	.0000	.0000	1.0000

4.3 Design and Fabrication of the Gasifier Simulator (Hot Model)

4.3.1 Gasifier Simulator (Hot Model) Body Design

The gasifier simulator (hot model) body is made of carbon steel pipe of 24-inch high and the outside diameter is 8-inch. The thickness is 0.25-inch as shown in Figure 28. The electric heating coil was installed inside the gasifier chamber. The electric heating coil is made by a specialized heating element design and manufacturing company. The heating element of the heating coil is L17-10C nichrome wire coil which can heat the inside material up to 1200 °C (2192 °F) with 3 Kw of inputted electric power. The wire coil is held and insulated from the conducting gasifier wall using the ceramic insulator which is built in the refractory layer. The operating temperature will be maintained at the range of 800-1200 °C (1472 - 2192 °F) for the experiment.

The refractory layer was attached to the inner side of the chamber wall to maintain relative high temperature which can simulate the real gasification environment. A certain amount of bars were welded to the wall to hold the refractory layer. The boiler refractory cement was used as the refractory material. The heat conduction coefficient is 0.8 w/(m °C). The small amount of heat will be transferred to the outside, which can keep the inside temperature at relatively steady state. The refractory layer thickness is determined by the following equation [1].

$$\frac{d_2}{d_1} = \exp(2 * \pi * \lambda * (T_1 - T_2) / Q)$$
 where d_1 and d_2 are the inner and outer diameter of the refractory layer, λ is the heat conduction coefficient of the refractory material, T_1 and T_2 are the inner and outer side temperature of the refractory layer, respectively, and Q is the heat conducting heat loss.

The upper and bottom flanges were welded at the end of the chamber wall. The respective blind flanges are made to seal the gasifier simulator (hot model). On the upper blind flange, two holes were drilled for the electric heating coil.

4.3.2 Heat Exchanger Design

The water heat exchangers were made of copper coil of 0.25-inch diameter. The copper coil was wired to the outside of the chamber. Cooling water is pumped through the copper coil and the high speed water could be carried out the heat. This type of heat exchanger maintains high efficiency heat exchanger because of high heat conduction materials and high fluid flow rate. The outside wall temperature could reach 43.3 °C (110 °F). The water speed could be controlled by the switch.

4.3.3 Temperature Sleeve Design

The temperature probe sleeve was designed as shown in Figure 29. The sleeve tube is 0.75-inch inner diameter with 0.125-inch thick and 7-inch long. A flange is welded to the end of the tube. The respective blind flange holding the probe is screwed to this flange. The probe is fixed at the center of the sleeve. Another tube with the same size is welded vertically to the sleeve. The cooling air is introduced through this pipe periodically to reduce the sleeve temperature. The sleeve is made of stainless steel which can stand high temperature.

4.3.4 The Fabrication of the Gasifier Simulator (Hot Model)

The detailed design of the gasifier simulator (hot model) was carefully prepared for the fabrication. The gasifier simulator (hot model) main body, the temperature sleeves, and

accessories including flanges, insulation, heat exchangers were fabricated carefully based on the detailed part designs, which was collaborated by the private fabrication company- K&C Welding Inc. Morgan research laboratory staffs have worked closely with the fabrication company for the assurance of the fabrication quality. Figures 30-32 show the pictorial view of the gasifier simulator (hot model), the sleeve and the thermocouple.

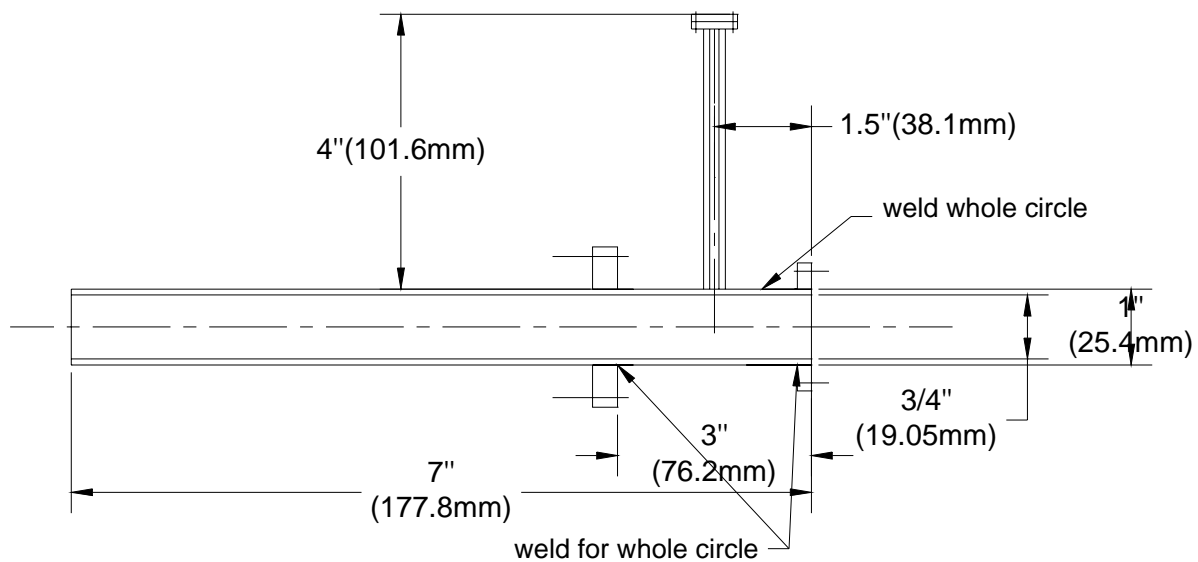


Figure 29. The Schematic Diagram of the Temperature Sleeve

Figure 30 The Gasifier Simulator (Hot Model) Test Facilities

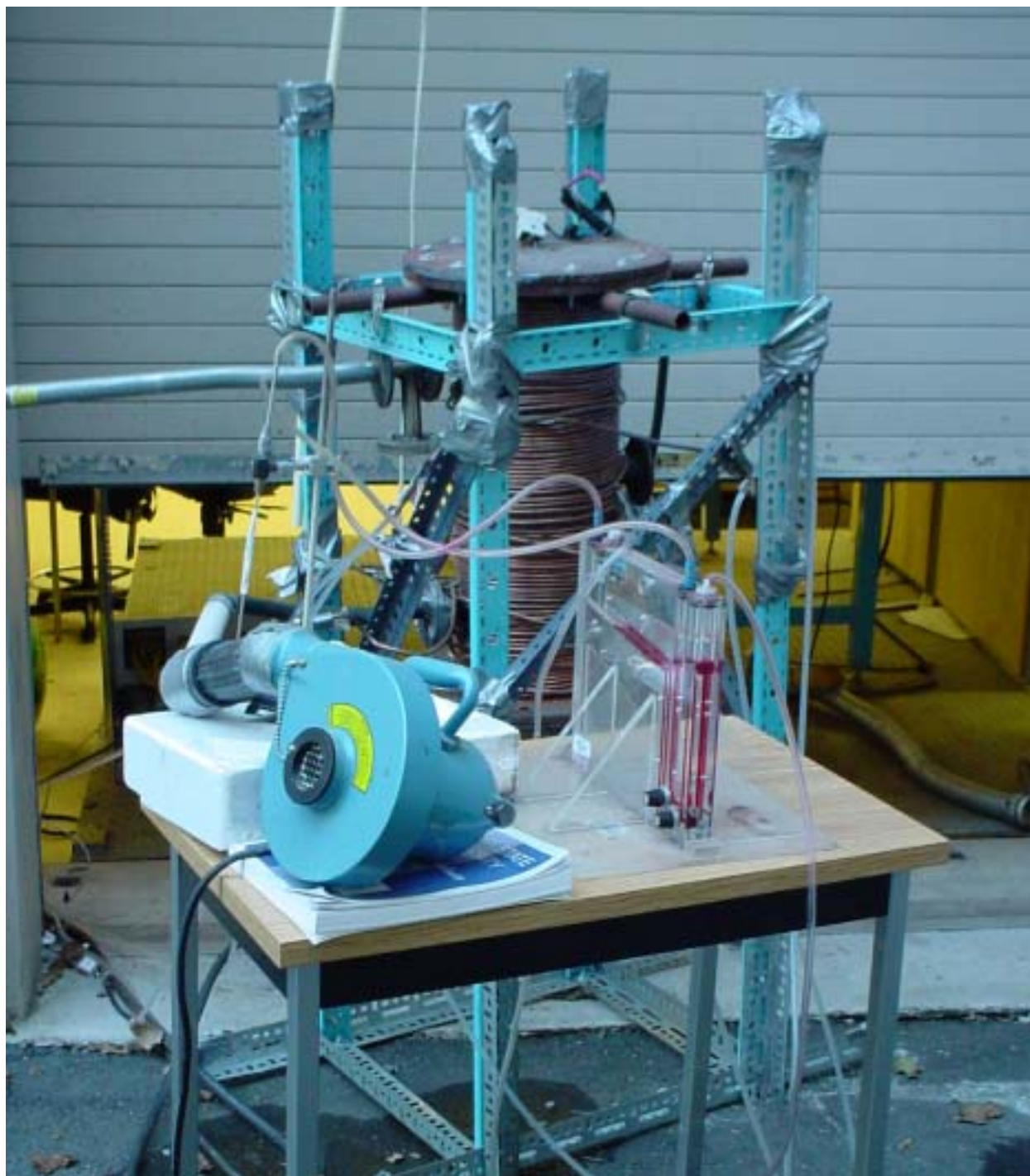


Figure 31 The Sleeve for the Gasifier Simulator (Hot Model)



Figure 32. The Thermocouple Probe (K-Type) for Gasifier Simulator (Hot Model)



5. CONCLUSIONS

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

1. The gasifier simulator (cold model) test along with the compressed air purging system could contribute to the accurate temperature measurements.
2. The ultrasonic device was implemented for the feasibility study of the cleaning applications in the gasifier.
3. The room temperature had significant impacts on the temperature measurement; hence, the room temperature needs to be normalized.
4. Linear and nonlinear regression methods are important tools to predict the temperature distributions in the gasifier simulator (cold model).
5. Nonlinear regression had a better performance in the prediction of the temperature changes in the gasifier simulator (cold model).
6. The gasifier simulator (hot model) design and fabrication have been successfully completed. All the design requirements have been met based on the system test.
7. The preliminary test data on the gasifier simulator (hot model) were obtained during the system test in the hot model.

REFERENCES

1. Coal Process and Pollution Control, Thomas F. Edgar, Gulf Publish Company, 1983.
2. http://www.fe.doe.gov/coal_power/special_rpts/market_systems/market_sys.shtm.
3. <http://www.netl.doe.gov/coalpower>.
4. G. Löffler, S. Kaiser, K. Bosch and H. Hofbauer, Hydrodynamics of a dual fluidized-bed gasifier—Part I: simulation of a riser with gas injection and diffuser, Chemical Engineering Science, Volume 58, Issue 18, September 2003, Pages 4197-4213.
5. Duan Y., Investigation into coal gasification in an industrial jetting fluidized bed gasifier, Fuel and Energy Abstracts, Volume 43, Issue 4, July 2002, Page 249.
6. S. C. Bhattacharya, San Shwe Hla and Hoang-Luang Pham, A study on a multi-stage hybrid gasifier-engine system, Biomass and Bioenergy, Volume 21, Issue 6, December 2001, Pages 445-460
7. Lee, S.W., "Effect of Solid-Bed Particles on the Material Wastage of In-Bed Tubes in the FBC", Presented at Fluids Engineering. Annual Conference & Exhibition, South Carolina, August 13-18, 1995, Book FED-Vol. 228, pp. 191-194.
8. Lee, S.W., and B.Q. Wang, "Erosion of AISI 1018 Steel and Several Thermal Sprayed Coatings under Simulated In-Bed Tube Erosion Conditions of Fluidized Bed Combustors", presented at 13th Int'L Conference FBC. Kissimmee, FL, May 7-10, 1995, Book FBC-Vol. 2, pp. 1427-1432.
9. Lopamudra Devi, Krzysztof J. Ptasinski and Frans J. J. G. Janssen, A review of the primary measures for tar elimination in biomass gasification processes, Biomass and Bioenergy, Volume 24, Issue 2, February 2003, Pages 125-140
10. Carlson C. P. Pian and Kunio Yoshikawa, Development of a high-temperature air-blown gasification system, Bioresource Technology, Volume 79, Issue 3, September 2001, Pages 231-241.
11. <http://www.clarkson.edu/~microlab/Ultrason.htm>.
12. Yourong Liu, Traugott E. Fischer and Andrew Dent, Comparison of HVOF and plasma-sprayed alumina/titania coatings—microstructure, mechanical properties and abrasion behavior, Surface and Coatings Technology, Volume 167, Issue 1, 1 April 2003, Pages 68-76.
13. Montgomery, D. C., Design and Analysis of Experiments, 4th Edition, 1997.

RESEARCH CONTINUATION

The progress of this project has been on schedule. The systematic tests will be continued in the gasifier simulator (hot model). The ultrasonic cleaning application for the gasifier simulator (hot model) will be implemented. The analysis of test results will be conducted using the design of experiments (DOE) and regression analysis methods.