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EMISSIONS PERFORMANCE OF A NOVEL COMBUSTOR BURNING SHREDDED WOOD

C. Lindsey
ANTARES Group Incorporated
Landover, Maryland, USA

M. Sawyer
Contractor with Applied Research Associates, Inc.
at Air Force Research Laboratory (AFRL),
Airbase Technologies Division (RXQ)
Florida, USA

A. Schmidt
ANTARES Group Incorporated
Landover, Maryland, USA

P. Aubrey
Clean Flame Energy
Scarborough, ME

A. Webster
formerly with Clean Flame
Energy Scarborough, ME

ABSTRACT[1,2]

The Air Force Research Laboratory, Airbase Technologies Division (AFRL/RXQ) is engineering and evaluating the Transportable Waste-to-Energy System (TWES). This trailer mounted system will convert military base waste and biomass waste streams to useful heat and power. The Department of Energy (DOE) Federal Energy Management Program (FEMP) is a TWES funding partner. The first stage of the project is a suspension-type combustor (furnace). The furnace has been built and tested. A key feature of the furnace system is its unique patented combustion coil design. The design is intended to maximize ablative heat transfer by increasing particle residence time near a radiant ignition source. The innovative features of the design are targeted at ensuring that the system can be highly fuel-flexible to convert a variety of biomass and other waste streams to energy while demonstrating very low emissions.

In 2008, the unit underwent two days of emissions stack testing using established Environmental Protection Agency (EPA) testing protocols. During the testing, extensive real-time data were also collected. This paper presents the data and corresponding analysis of the recent emissions testing performed while utilizing dry wood chips as a control fuel. Detailed emission comparisons are presented using publicly available information from commercial units and from a similarly sized experimental system for small biomass combustion. Key combustion efficiency factors, such as carbon monoxide emissions and nitrogen oxide emissions are presented. The authors also provide commentary on the results for next generation units and the use of this mode of energy conversion for small scale systems.

INTRODUCTION

The Air Force Research Laboratory, Airbase Technologies Division (AFRL/RXQ) is engineering and evaluating the Transportable Waste-to-Energy System (TWES). This trailer mounted system will convert military base waste and biomass waste streams to useful heat and power. The innovative features of the design are targeted at ensuring that the system is fuel-flexible with the ability to convert a variety of biomass and other waste streams, including plastics, to energy while demonstrating very low emissions. In 2008, the unit underwent two days of emissions stack testing using established EPA testing protocols. During the testing, extensive real-time data were also collected.

NOMENCLATURE

A/F	air/fuel ratio, mass basis
Est	estimate
FGR	flue gas recirculation
HHV	higher heating value of fuel (Btu/lb)
kg/GJ	kilogram of pollutant per gigajoule of fuel burned
kWt	kilowatts of thermal energy

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[2] This document includes color graphs and photos. It is best viewed and printed in color.

NA	information not available
NO_X	oxides of nitrogen
Pct	percent distance from entrance of combustion coil, used in graphs
PM	particulate matter, e.g.: ash escaping in exhaust gases
ppm	parts per million
TE	temperature element, i.e.: thermocouple
TWES	Transportable Waste-to-Energy System

DESCRIPTION OF THE TWES

The TWES will be built on multiple trailers for mobility. The first TWES trailer has been built. It includes fuel processing equipment, a fuel storage and conveyance system, and a unique furnace. A photo is provided in Figure 1. With respect to operation, the system is designed to burn solid waste, which includes processing it to a size suitable for conversion in the furnace. Future TWES trailers will include water treatment, a heat recovery steam generator, steam engines, electric generators, an absorption chiller, a cooling tower, and other heat exchangers.

Figure 1: Furnace portion of the Transportable Waste-to-Energy System

During full operation of the furnace, fuel is sent through the fuel sizing equipment (shredder) and transported pneumatically to a fuel hopper. Ready-to-fire fuel is then reclaimed from the hopper using a conveyor and a rotary airlock. The prepared fuel is transported pneumatically to and then through the TWES combustion coil. Transport air serves to provide primary combustion air. Air is not preheated before entering the furnace. The coiled pipe inside the furnace is the primary combustion chamber. The coil entrance is at the top of the furnace. The coil ends inside and at the bottom of the furnace, so after exiting the coil, combustion gases rise through the furnace's central chamber. This is the secondary combustion chamber. Additional air (secondary air) can be introduced into the bottom of the furnace. The flow path of the furnace, excluding the shredder, is shown in Figure 2. Two blowers feed air; although, the simplified diagram shows only one.

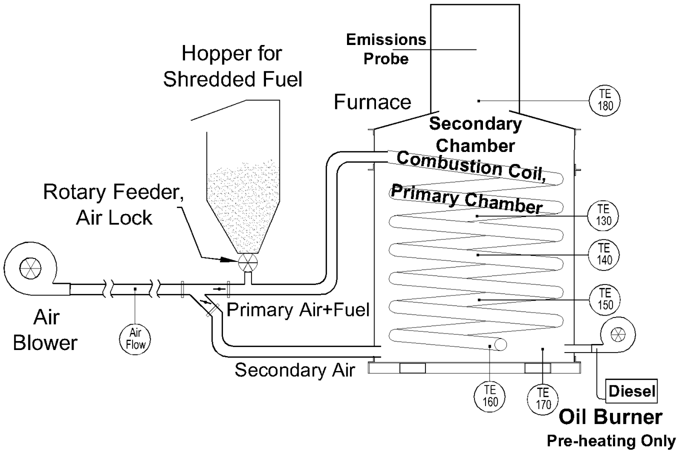


Figure 2: Process Flow Diagram of TWES Furnace, simplified

The hot combustion gases generated in the furnace are exhausted out the unit's stack. As mentioned earlier, a heat recovery steam generator is being designed to recover this heat in a small tri-generation system. Based on analytical data, the completed TWES is predicted to operate with an overall efficiency of 19% (heating value of fuel vs. total useful energy output) in the cooling mode. This assumes an operating condition of 500 lb/hr of mixed solid waste typical to a military base and a 158 kWt (45 tons) cooling load. The TWES will produce enough electricity to operate its equipment. Net positive electricity could be produced if the cooling load were reduced. This cooling load is near the design condition for a small demonstration project planned for Tyndall AFB.

TEST OBJECTIVES AND METHODS

Early in 2008, the project team developed a test protocol for the unit with the objective of demonstrating the performance of the TWES furnace (operations and emissions) over several days at multiple loads and for longer periods than in prior tests. In addition, prior tests had indicated that the furnace was capable of generating combustion temperatures that were well beyond the metallurgy of the combustion coil at fuel input rates above 125 pounds per hour. The project team sought to vary the amount of air and the split between primary and secondary air to maintain a cooler combustion temperature profile.

Experiments and stack testing were conducted across a three day period in July 2008. During two of these days, a professional stack emission testing contractor was on-site to measure important stack emissions in accordance with EPA stack test protocols. The contractor conducted tests for particulate, carbon monoxide, sulfur dioxide, and nitrogen oxide emissions from the furnace unit.

Testing procedures followed were according to Methods 1, 2, 3A, 5, 7E, 10, and 202. These methods can be found in the U.S. EPA Emission Measurement Center's web site (**www.epa.gov/ttn/emc/**).

During the tests, the furnace was fed dried, shredded wood (animal bedding) as fuel. This fuel was pre-processed to a size that facilitated its direct use in the system. Although the TWES furnace trailer is equipped with on-board fuel processing, the project team decided to bypass the shredder to expedite the experiments and focus on combustion performance.

The composition of the fuel was expected to remain fairly consistent during the tests. Even so, the project team collected numerous fuel samples. Results of the fuel analyses conducted on grab samples taken during the test are provided in the table below.

Table 1: Fuel Analyses

Test Series	Sample ID	HHV (Btu/lb)	Ultimate %						
			Moisture	Carbon	Hydrogen	Nitrogen	Sulfur	Ash	Oxygen
Low-Load Tests 1-3	02A	7,787	10.41	48.00	5.74	0.10	0.02	0.43	35.30
	04A	7,853	10.11	47.83	5.76	0.09	<.01	0.42	35.79
Mid-Load Tests 4-6	06A	7,548	12.91	46.22	5.55	0.07	0.02	0.37	34.86
	08A	7,379	14.04	45.87	5.51	0.09	0.02	0.35	34.12

In addition to the furnace emissions, other key variables measured during testing included the following:

- Fuel flow rates
- Air flow rates
- Temperatures along the combustion coil inside the furnace and at the exit of the stack

The current system is not fitted with gravimetric feeders, so fuel flow was measured using speed and geometry data for the conveyor feeding the rotary airlock. Air flow was instrumented using annubar sensors and cross checked using manufacturer blower curves and overall flow data from the stack testing. The total air flow separated into two paths, one for primary, and one for secondary combustion air. Butterfly valves roughly regulated the flow (Figure 2). The total air flow was measured, but the separate flow paths for primary and secondary combustion air were too short to be accurately instrumented. The primary path also contained shredded fuel. Temperature profiles were measured using thermocouples throughout the system including inside the furnace and inside the combustion coil itself.

During the tests, air and fuel flow rates were varied to accommodate two furnace load conditions: low-load and mid-load. Table 2 provides average flow rate data for the six emission tests.

Table 2: Flow Rate Data for Emission Tests

	Load Condition	
	Low Tests 1-3	Mid Tests 4-6
Avg. Fuel Flow Rates (lb/hr)	157	199
Avg. Air Flow Rates (lb/hr)	3,334	3,719
Avg. A/F Ratio (lb-air/lb-fuel)	21	19
Avg. Heat Input (kWt)	359	425
Avg. Exhaust Temp (C)	697	715
Avg. Residence time, est. (s)	0.9	0.7

TEST RESULTS

Based on analysis and data collected from past tests, it was anticipated that the combustion coil inside the furnace would experience a temperature gradient. In past tests, the fuel input to the furnace was limited since portions of the coil would begin to heat beyond recommended material temperatures. A key objective of the tests was to determine the extent that redirecting (either through the coil or to the bottom of the reactor) and/or increasing the air flow rate into the unit would moderate coil temperatures and allow for an increased fuel flow.

Table 2 shows the average fuel and air flow rates used during the course of the tests. The project team was able to keep exhaust temperatures relatively stable by increasing overall air flow rates to the values listed in the table. During one day of operation, emissions Tests 1, 2, and 3 were run at low-load, and on the following day, Tests 3, 4, and 5 were run at mid-load. Except for a few brief interruptions, the combustor operated throughout each day of testing.

The following exhibits present three-dimensional plots of the real-time temperature data taken at various points in the TWES unit for each test. The following information is valuable in reviewing these plots.

- Each plot corresponds to a stack test conducted by the emissions testing contractor.
- TE-130, TE-140, TE-150, TE-160 are thermocouples in place to measure the temperatures of the combusting flow inside the coil. They are uniformly spaced from the start of the coil as diagramed in Figure 2.
- TE-170 was located at the bottom of the reactor outside the combustion coil
- TE-180 is a thermocouple located at the entrance to the reactor stack and measures the initial stack gas exhaust temperature.
- TE-130 failed during the course of Test 5 and is not shown for Test 5 or Test 6. TE-130 is the thermocouple located at 25% of the total coil length, measured the furnace entrance.

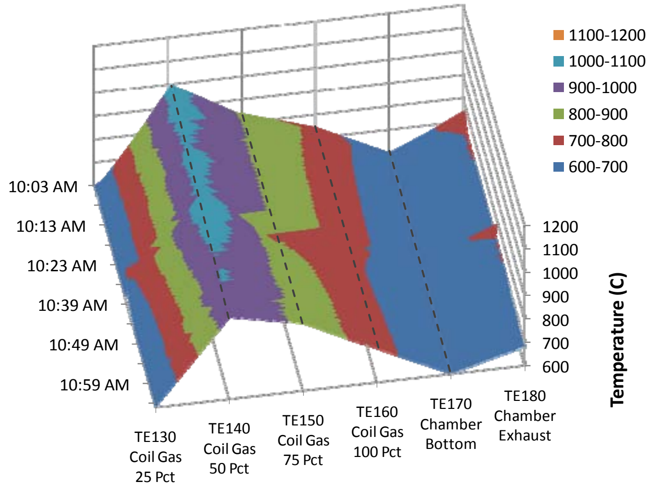


Figure 3: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 1 (Dashed lines were manually projected/drawn on the plotted surface.)

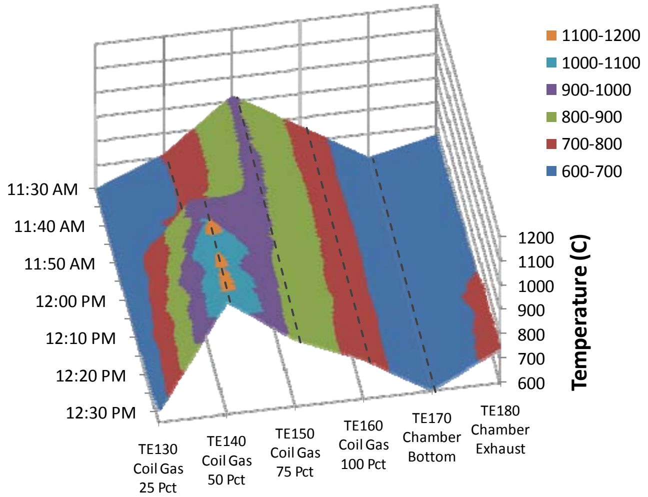


Figure 4: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 2

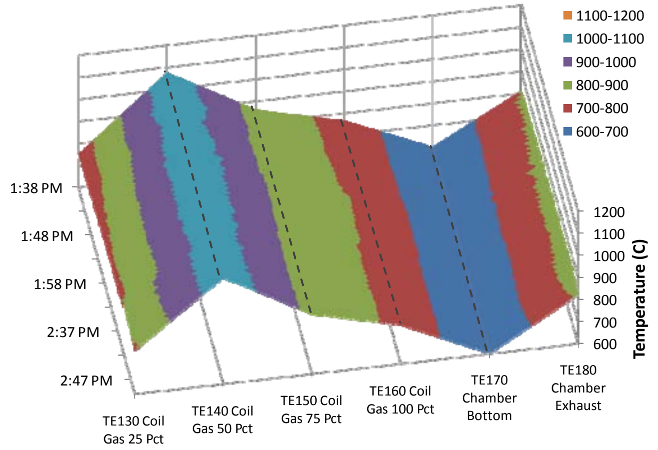


Figure 5: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 3

As can be seen in Figure 3, Figure 4, and Figure 5, the highest temperatures experienced in the system during the low-load tests were found at approximately the half way point of the combustion coil, TE-140. In Figure 4 Test 2, a change is indicated at about 11:50AM, the result of a change in operating conditions. Note that in the second half of Test 2, temperatures spiked for a few minutes at various times. These temperature excursions roughly correspond to temporary increases in fuel flow as the project team attempted to adjust firing conditions.

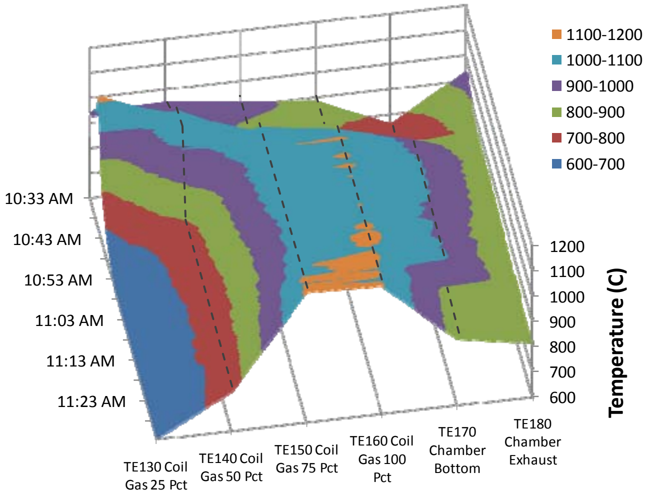
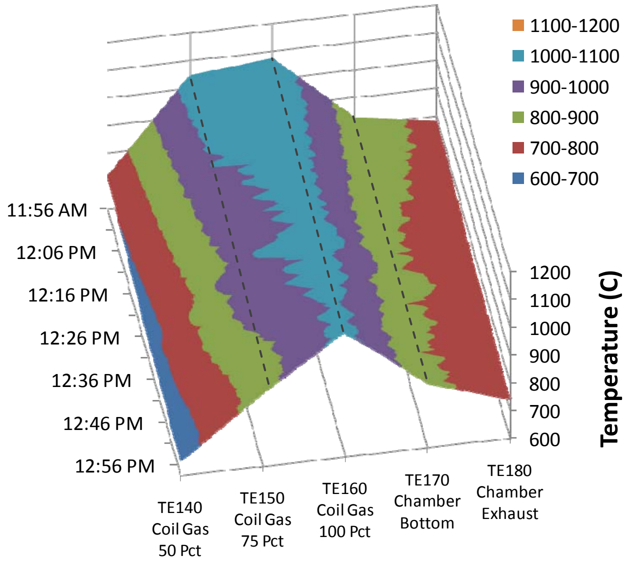
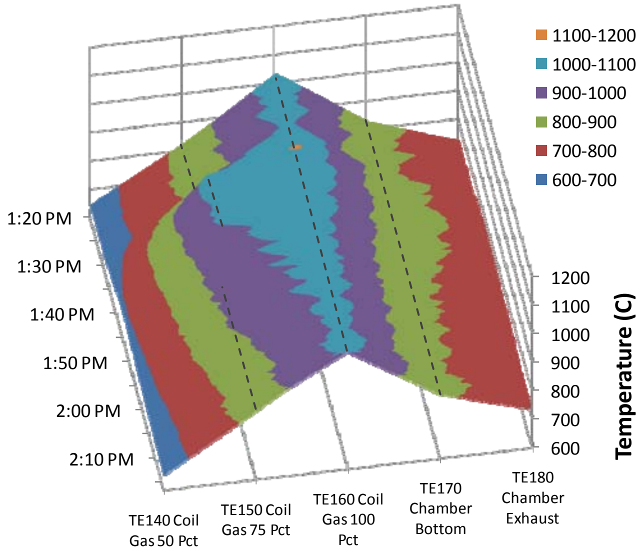


Figure 6: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 4



NOTE: TE 130 thermocouple failed during this test at 11:44 AM. As such, this data is not shown here.

Figure 7: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 5



NOTE: TE 130 thermocouple failed during the last test, at 11:44 AM. As such, this data is not shown here.

Figure 8: Temperature Profile of Gases inside the Coil, the Primary Combustion Chamber - Test 6

In mid-load Tests 4, 5, and 6 the project team adjusted the combustion air flow upward in two important ways. First, additional combustion air was provided by the blowers because the fuel rate increased. Even so, the air/fuel ratio was less than during low-load Tests 1, 2, and 3. Secondly and perhaps more importantly, a greater percent of the air was sent through the primary combustion coil and correspondingly less air was directed to the secondary path at bottom of the furnace. These adjustments resulted in the following changes in combustion behavior:

- The “hot spot” in the combustion coil moved down near the exit of the coil. In the mid-load tests (Figure 3, Figure 4, and Figure 5) the peak recorded combustion temperature was at the halfway point along the coil (TE-140). In the mid-load tests (Figure 6, Figure 7, and Figure 8), the peak temperature was recorded at the coil exit (TE-160).
- The observed flame exiting the coil became steady and regular with superior particle burnout; whereas, in Tests 1, 2, and 3, the flame front was unsteady and the system seemed to “pulse” more.

The ability to move the coil “hot spot” was of interest to the project team because it was believed this could be important to controlling exhaust gas temperatures and possibly emissions.

Ultimately, one of the parameters most important to the design of the TWES steam generation system is the average stack gas exit temperature. It is important to note that in all of the plots, the stack gas temperature, measured by TE-180, was not the highest temperature measured. To investigate this further, the team prepared plots of the difference between the hottest coil temperatures recorded over time (regardless of where the peak occurred in the coil) and the associated stack gas temperatures. Figure 9 and Figure 10 show the results of that analysis.

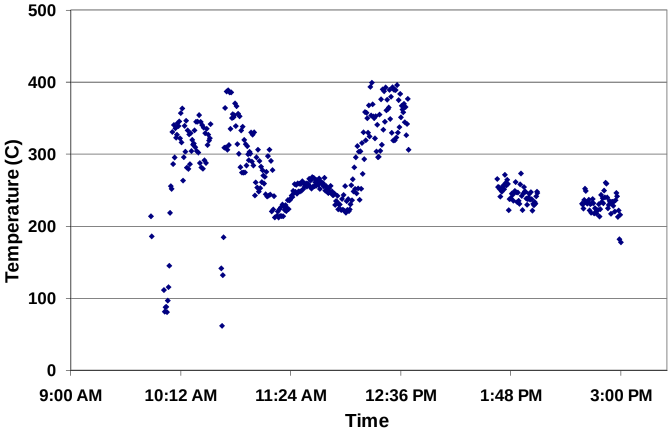


Figure 9: Difference between Hottest Furnace Gas Temperature and Exhaust Gas - Low Load

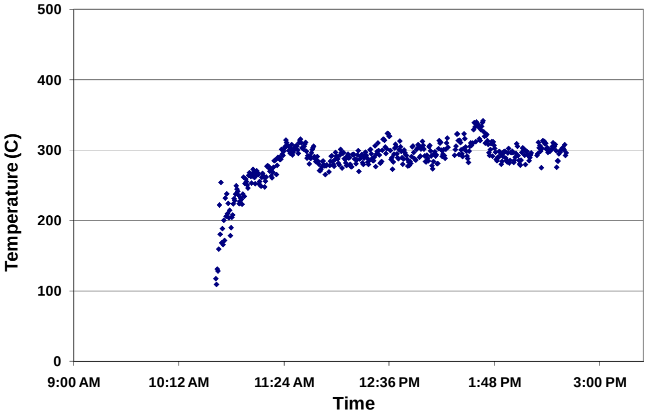


Figure 10: Difference between Hottest Furnace Gas Temperature and Exhaust Gas - Mid Load

The analysis shows that there is a consistent and substantial temperature differential between the peak coil temperatures and the exhaust gas temperature. Although the temperature differential was more erratic during the first three tests (some portion of this was due to “tuning” that was being conducted on the fly), overall and especially in the latter tests, the difference was very clear and approximately 300 degrees Celsius. This is significant since the project team prefers to operate the unit near 1,100°C or less to remain below the upper limit of the coil metal. For the purpose of designing the steam generation equipment, it would be ideal for this differential to be smaller, corresponding to a hotter exhaust temperature.

STACK EMISSIONS RESULTS

The results of the stack testing by the emissions contractor are summarized in two columns of Table 3. In addition, the table includes values from AP-42 (an EPA guidance document regarding emission factors for stationary emission sources) [1] and some results from combustion tests that were performed by TVA in the early 1980s on a small biomass combustion unit [2]. The TVA test system was of a similar heat input scale as the furnace reported in this article, but wood was fed into the burner by hand. The pieces of wood were between 24 and 28 inches long. The TVA combustor was a prototype of a system intended to serve the commercial and residential market.

Table 3: Stack Test Results

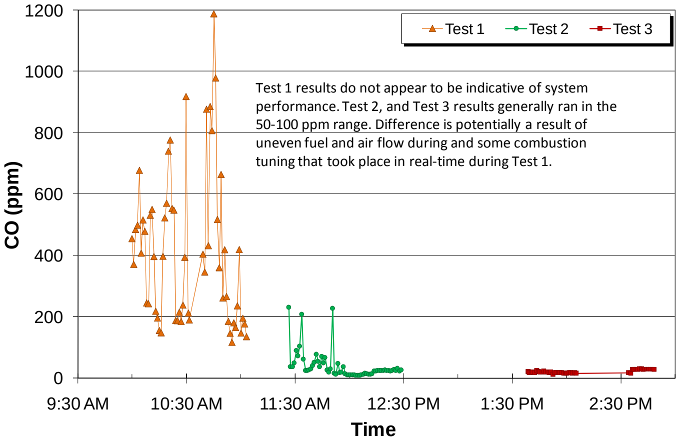
	Load Averages[1]		Comparison Data	
	Low-load	Mid-load	AP-42[3]	TVA[4]
Average Heat Input (GJ/hr)[2]	1.29	1.53	NA	0.4-0.6
Average Heat Input (kWt)	359	425	NA	111-167
Particulate Emissions (kg/GJ)	0.17	0.14	0.17	0.08
CO Emissions (kg/GJ)	0.17	0.19	0.26	2.12
CO Emissions (ppm)	169	180	NA	NA
NO$_X$ Emissions (kg/GJ)	0.08	0.12	0.21	0.07
NO$_X$ Emissions (ppm)	43	68	NA	NA
SO$_2$ Emissions (kg/GJ)	0.01	0.01	0.01	0.01
SO$_2$ Emissions (ppm)	2	3	NA	NA

Notes: 1) AST stack test data for TWES Furnace
2) Based on ultimate analysis data and fuel mass flow rates
3) EPA, emissions from stationary sources; small wood-fired boilers using dry wood pp. 1.6.6-7
4) Wood-fired Boiler Test Report, TVA, August 1983
5) All emissions uncontrolled

The data presented by EPA is useful in establishing an understanding of a permitting authority's reference point for a wood power plant. However, most wood-fired generation plants are considerably larger than the TWES and the combustion characteristics of larger boilers are not necessarily directly comparable. As a result, the authors sought to locate combustion data from sources of a similar size to the TWES.

In the early 1980s, the Tennessee Valley Authority (TVA) conducted some emission testing for a small-scale, hand fed, commercial wood-fired boiler. These tests were conducted under a rigorous testing protocol. The data included emissions for wood fuel at several reference moisture contents and the heat input for the system when using dry wood was approximately 0.40 to 0.60 GJ per hour. This is approximately 1/3 to 1/2 of the rate fired in the TWES. So, the fuel rate for the TVA testing was similar to the TWES, certainly not the several orders of magnitudes of difference that are reflected in the AP-42 guidance.

Although the average emissions data presented above are useful in benchmarking emissions performance, additional information was gleaned from the real-time data. Of the data collected, CO and NO$_X$ were of the greatest interest[3]. Figure 11 and Figure 12 show the CO emissions recorded by the contractor during testing. Note that the CO emissions for Test 1 were considerably higher than those recorded for the balance of the low-load tests. These relatively high results may reflect the fact that the project team was still making adjustments to the air and fuel flow and the furnace may not have reached stable operating conditions. A similar behavior, although less pronounced, is noted in the NO$_X$ emissions recorded for Test 1 in Figure 13.



Test 1 results do not appear to be indicative of system performance. Test 2, and Test 3 results generally ran in the 50-100 ppm range. Difference is potentially a result of uneven fuel and air flow during and some combustion tuning that took place in real-time during Test 1.

Figure 11: CO Emissions - Low-load

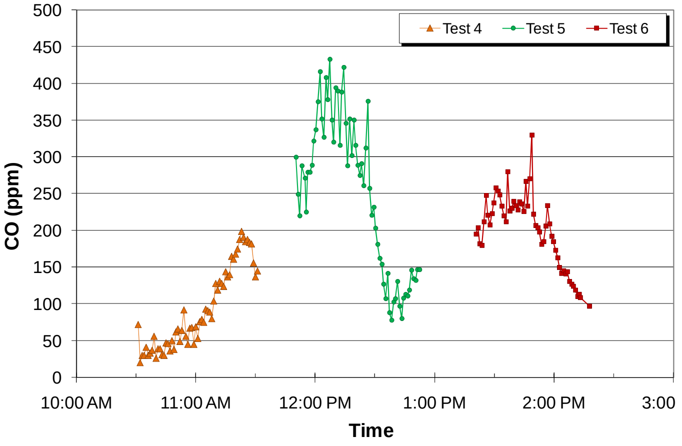


Figure 12: CO Emissions - Mid-load

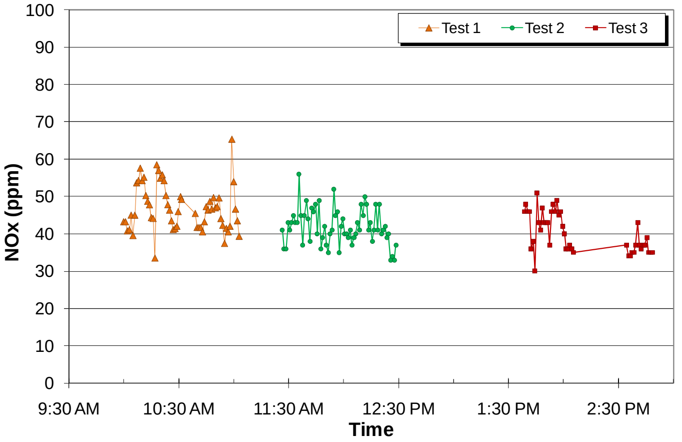


Figure 13: NO$_X$ Emissions - Low-load

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[3] Since biomass contains almost no sulfur, the SO$_2$ emissions were very low and no additional analysis of SO$_2$ is warranted.

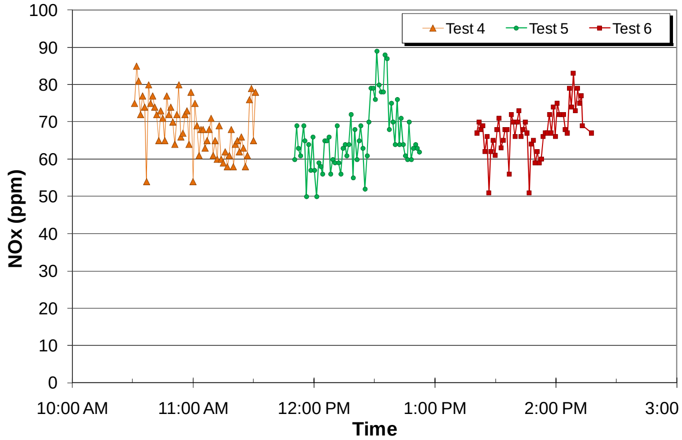

Figure 14: NO_X Emissions - Mid-load

Overall, the CO emission profile exhibited during the low-load test conditions was very good. Tests 2 and 3 exhibited very low emissions. Low CO emissions are typically indicative of complete combustion. Removing the Test 1 data from the low-load data set would considerably lower the average CO emissions; placing it below 40 ppm. However, the data in Table 3 includes all three low-load tests. The CO emissions recorded during the mid-load tests were clearly higher than the low-load results, but still very good when compared to much larger systems, and much lower than a system of like-scale, Table 3. However, there was considerable variation in the results within a particular load condition.

Additional comparisons between the TWES data and the EPA AP-42 expectations and also between the TWES and the TVA results will be presented in the Discussion section of this paper.

With respect to the observed variations in emissions, two additional points are worth making:

1. The project team made every effort to maintain consistent and stable operating conditions throughout the tests.
2. With the exception of a few fuel interruptions (several minutes each) the combustor operated throughout each days testing.

With operating conditions accounted, it is clear that the data indicate an undulation that is most apparent in Figure 11, but which can be observed in all of the tests to some degree.

The NO_X emission data recorded during the tests were considerably more consistent than the CO data, and each test within the load groupings was also very consistent. Given the stability of the results, it is clear that average NO_X emissions increased for the mid-load cases relative to the low-load tests. The change in NO_X was significant, approximately 50 percent, as shown in the data presented in Figure 13 and Figure 14 and summarized in Table 3.

DISCUSSION

During the testing, it became clear that the operation of the TWES requires careful balance of primary (transport) air, secondary air, and fuel flow. The temperature data presented suggest that nearly stable operating conditions and temperatures were achieved with higher fuel flows by adjusting the amount and balance of primary and secondary air. However, a certain amount of "tuning" was required during testing. Observations made while analyzing the data include the following:

1. The most stable flame conditions were observed in the mid-load tests when the peak system temperatures were pushed (via the addition of primary combustion air) towards the bottom of the combustion coil. However, this may have lead to higher CO and NO_X emissions. This operating condition also resulted in a peak coil temperature that was consistently 300°C hotter than the exhaust gas temperature (Figure 10).
2. In most of the plotted data presented, there is a noticeable undulation. This effect is the most pronounced in Figure 9 and Figure 11 but it appears subtly in several of the other data sets. During testing, the pneumatic fuel delivery system experienced some pulsing and it is clear that additional operational experience and tuning is required before completely stable operation will be achieved. Ideally, performance would reach a relatively steady state under steady fuel loading and air supply.

With respect to CO and NO_X emissions, the system performed very well based on available comparative data. However, it is clear that the CO emissions in the last three tests were higher than the first three. There may be several reasons for this effect.

1. The overall A/F ratio for the second series of tests was generally lower than for the first three tests, Table 2. As CO is associated with incomplete combustion, this may indicate that insufficient air was available in the second series of tests, the mid-load cases, to facilitate complete combustion. However, temperature data indicate that most combustion occurred in the coil, and the balance of air was adjusted to increase the percentage entering this primary combustion chamber. So, the "local" A/F ratio in the coil may have been similar to the first three tests. These concepts challenge the "insufficient air" argument.
2. A more likely cause: the correspondingly higher air flow rates used to burn the mid-load tests effectively reduced residence time. This could have led to poor burnout and the degradation in emissions.

Interestingly, CO and NO_X emissions in conventional boilers often move in opposite directions. This competition is due to the opposing effect that temperature has on CO and thermal NO_X. Typically, as furnace temperature goes up, CO goes down and NO_X goes up. However, on average, during the tests CO and NO_X both moved upward, as observed when comparing the results of the low-load tests followed by the mid-load tests in Table 3. Although there were discrete periods where they moved in opposite directions, they also did so counter intuitively relative to recorded temperatures. For example, in Test 4, CO increased, NO_X decreased, while the peak temperatures in Test 4 were some of the highest recorded. (Refer to Figure 12, Figure 14, and Figure 6.)

Part of the explanation may be related to the local A/F ratio in the primary combustion chamber. The fuel is initially exposed only to the primary/transport air as it travels down the combustion coil. Upon exiting the coil, secondary air causes continued combustion and dilution. This dilution is the primary reason that the overall exhaust gas temperature is not indicative of the peak temperatures experienced inside the combustion coil itself, where a large part, if not all the combustion is taking place. It is possible that local hot spots, not easily observed inside the combustion coil resulted in higher thermal NO_X formation with the added fuel. As stated earlier, a more stable flame was observed during testing for the mid-load tests. This certainly could have lead to higher average local temperatures.

The potential for "hot spots" to occur is important on a few fronts. First, they are important to metallurgy. Exceeding the rated conditions of the coil material could result in system failure. Second, it is possible that the relatively slight increase in average temperature noted between the two load conditions (refer to Table 2) may actually be masking a more distinct change in local temperatures. Note that the real-time temperature data for the mid-load condition presented in Figure 6 show several temperatures excursions into the 1100-1200 °C range, and Figure 8 has one brief high temperature excursion. In comparison, for the low-load condition, Figure 4 alone has a few data above 1100 °C. Of course, the higher fuel rate in the mid-load tests was a significant factor in its higher average temperatures. Lastly, the emissions data suggest that it is possible that incorrect system tuning or air balance could result in high NO_X formation rates and reduced carbon burnout. So, just as the system can exhibit low NO_X and CO in tandem, it can also exhibit high NO_X and CO, a combination to be avoided.

With respect to temperature control and emissions, it is possible that flue gas recirculation (FGR) may also be used to control the location and intensity of peak temperatures within the coil. This would require a relatively straight forward modification. In addition, the use of FGR has the virtue of a proven track record and substantial research to guide its application.

The exact cause for the undulating behavior of the real-time emissions is also not fully understood. Clearly the impact on CO emissions was more significant than it was on NO_X emissions. The project team believes this behavior may be related to fuel or air delivery or potentially complex combustion dynamics in the coil itself. Future tests will be needed to understand the behavior and hopefully optimize the system to lower the average emission rates further.

The TWES furnace performed equal to or better than EPA expectations [1] (Table 3) for PM, CO, and SO_2, while performing very well with respect to NO_X. The NO_X results are not surprising given that combustion temperatures for the unit were held to 1,100 C or less during the tests, with some brief exceptions. Lower firing temperatures have a positive impact on thermal NO_X formation and similar results are found in units that stage combustion air to achieve similar firing temperatures.

The results shown above indicate that on average the TWES boiler performed similarly to a smaller wood-fired TVA unit [2] with respect to NO_X emissions. However, PM emissions for the smaller unit tested by TVA appear to be better. Some part of this may have to do with the fact that the TWES does not currently incorporate any ash removal. The TWES team expects that the installation of a downstream multi-clone (a gas-solid separator consisting of multiple cyclones) will lower these emissions significantly. Additionally, future TWES units can be constructed with bottom ash removal. With respect to CO emissions, it appears that the TWES system demonstrated better CO to CO_2 conversion than the small TVA unit.

CONCLUSIONS AND NEXT STEPS

The tests conducted for the TWES system provided valuable insight into the system's operation and emission performance. Specifically, the system is capable of demonstrating low CO and NO_X emissions while operating on wood and maintaining acceptable combustion temperatures at low- and mid-load fuel rates. Using the data collected in these tests, the project team is developing a heat recovery steam generation system that will be used to convert the existing furnace system into a small tri-generation unit, providing heat, cooling, and electric power. Testing for the expanded system is planned for fall 2009.

The project team is also using the data to develop specifications for the next generation furnace. Proposed future systems incorporate greater air flow capacity, gravimetric fuel measurement systems, fly/bottom ash handling systems, and possibly FGR for temperature and emission control.

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