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MONITORING POWER PLANT EFFICIENCY USING THE MICROWAVE-EXCITED PHOTOACOUSTIC EFFECT TO MEASURE UNBURNED CARBON

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ABSTRACT

Three test instruments are being evaluated to determine the feasibility of using photoacoustic technology for measuring unburned carbon in fly ash. The first test instrument is a single microwave frequency system previously constructed to measure photoacoustic signals in an off-line configuration. A second off-line instrument was constructed based in part on lessons learned with the first instrument, but which also expands the capabilities of the first instrument. Improvements include a control loop to allow more constant microwave power output and an ability to operate over a range of microwave frequencies. The third instrument, the on-line version of the fly ash monitor, has been designed, constructed, and initial efficiency tests have been conducted on the monitor's electrical components.

Design and construction of the on-line fly ash monitor has been completed, as well as supporting apparatus that includes the independent support stands for the fly ash feeders and customized bottom hopper and feeder system. Modifications were made to the original design of the on-line monitor to improve the flow of fly ash through the monitor, and improvements were made to the diaphragm assembly where the accelerometer is to be mounted. The electrical components that provide and regulate the microwave source has been completed. Microwave leakage tests have also been completed to determine the robustness of the on-line monitor

Keywords: fly ash, carbon monitor, unburned carbon, boiler instrumentation

EXECUTIVE SUMMARY

The objective of this project is to explore the use of the microwave-excited photoacoustic (MEPA) effect for quantitative analysis of granular and powdered materials, and to develop an on-line carbon-in-ash monitor. The three steps to achieving this objective include: 1) designing a single microwave frequency, off-line instrument as part of proof-of-concept evaluations; 2) construction of a microwave spectrometer based on MEPA used to evaluate a variety of industrial important powders, including fly ash and pulverized coal; and 3) design and construct an on-line monitor that used MEPA technology. The instruments for steps 1 and 2 have already been completed, tested, and evaluated, and the research is currently focused on step 3, the on-line fly ash monitor.

Support structures for the MEPA system has been completed and the monitor mounted on it such that it is independently supported from the volumetric feeders that control the flow rate of the fly ash into and out of it. Plastic skirts connect the feeders to the fly ash monitor to minimize the transfer of mechanical vibrations.

Significant modifications were made to improve the flow of fly ash through the on-line fly ash monitor, while still maintaining minimal radio frequency (RF) leakage. The entrance section was modified from a pipe to a chamber divided by a baffle, similar to the bottom section of the fly ash monitor. Different bottom hopper designs were developed in an attempt to prevent bridging of the fly ash because as fly ash flows as packed bed, the fly ash at the bottom compacts, reducing the efficiency of the bottom feeder auger to “pick-up” the fly ash. The best method to prevent the fly ash from bridging involved installing a second shaft that was ganged off the main shaft of the bottom feeder, and narrow spindles were attached to this second shaft that agitate and stir the fly ash, preventing it from compacting. The customized bottom hopper is made of clear acrylic so that the flow of the fly ash could be visually inspected, and the auger tube is made of UHMW polyethylene. The bottom feeder operates at a maximum speed of 470 $cm^3\ min^{-1}$, and the upper feeder’s flow rate can be adjusted to match the speed of the bottom feeder.

The electrical components of the on-line fly ash monitor have been assembled. A Si-Flex SF1500L Low-Noise Accelerometer from Applied MEMS, Inc. has been mounted on a thin diaphragm of aluminum that will be used to measure the thermo-elastic response of the fly ash. Additional electrical components used to generate the 1 GHz microwaves that will be used to induce a thermo-elastic response in the fly ash have mounted in a utility box that will be mounted on the large Uni-Strut support stand of the fly ash

A Radio Frequency (RF) leakage test was conducted to confine the RF safety level as defined by IEEE Standard for Safety Levels with respect to Human Exposure to Radio Frequency Electromagnetic Fields 3 kHz to 300 GHz (IEEE C95.1-1991). To measure the RF leakage of the fly ash monitor, 1 watt of RF power was applied into the fly ash monitor. The fly ash monitor was scanned at different spots to determine the RF leakage using a 7.6-cm monopole antenna which connected to a HP8563E spectrum analyzer. The largest power density measured was 1.35×10^{-9} mW cm^{-2}. This value is significantly lower than the required safety level 3.33 mW cm^{-2} for a controlled environment.

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INTRODUCTION

The objective of this project is to explore the use of the microwave-excited photoacoustic (MEPA) effect for quantitative analysis of granular and powdered materials. The focal point of the research centers on the measurement of unburned carbon in fly ash, an important parameter in the electric utility industry used to determine plant efficiencies. The culmination of this project will be an on-line carbon-in-ash monitor for coal-fired power plants. However, evaluations also will be made on other powdered solids, particularly coal.

The approach to this project includes work with three MEPA instruments. The first instrument is a single microwave frequency, off-line instrument built at Iowa State University as part of proof-of-concept evaluations. It is being used to evaluate precision and accuracy of the MEPA technique. The second instrument is being constructed as a microwave spectrometer based on MEPA. It will be used to evaluate a variety of industrial important powders, including fly ash and pulverized coal. The final instrument will be built based on the results of work with the previous two instruments and will be used as an on-line monitor of unburned carbon in fly ash.

EXPERIMENTAL

Construction and operation of the on-line fly ash monitor – Mechanical components.

Figure 1 is a photograph of the on-line fly ash monitor system, including the support stands and feeders. The instrumentation used to generate and monitor the microwaves, and to measure the thermo-elastic waves generated by the microwaves are not shown. At the top of the figure is the blue Tecweigh CR5 volumetric feeder with a stainless steel hopper mounted on a Uni-Strut support stand. Attached to the end of the Tecweigh feeder is a plastic skirt that acts as a soft, flexible seal between the feeder and the top of the fly ash monitor.

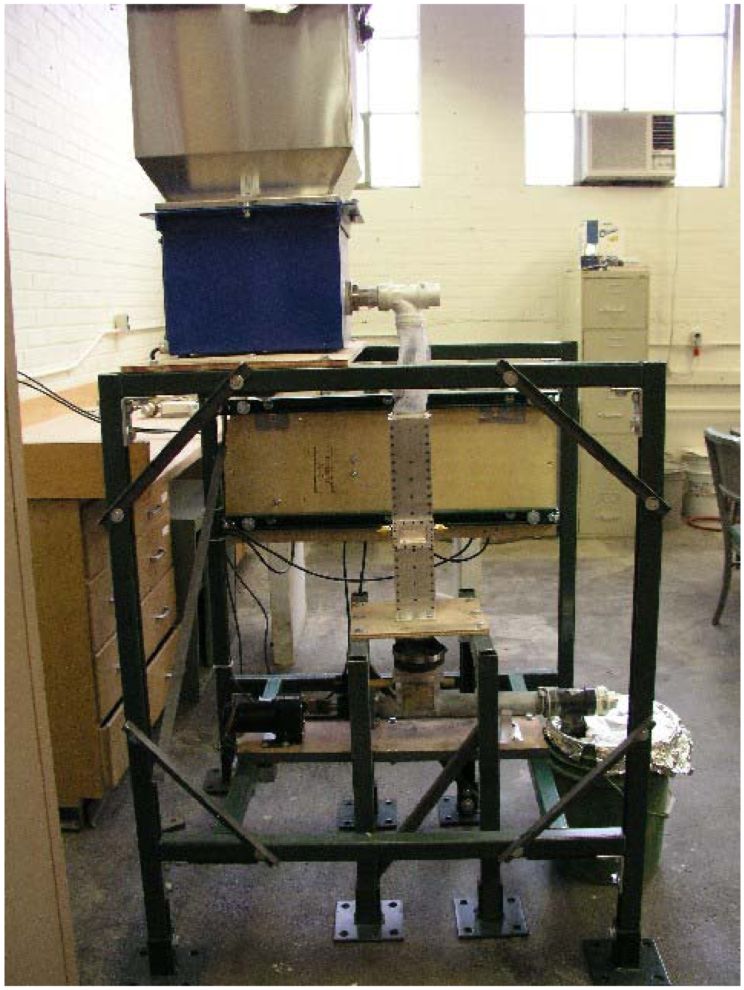

Figure 1. On-line fly ash monitor and supporting apparatus

The original design of the on-line fly ash monitor used a 15-cm-long aluminum pipe as the entrance section of the fly ash monitor, but the flow of fly ash through the pipe often clogged, so the entrance section was changed to mirror the design of the bottom section. Contained within the entrance section is a baffle to prevent microwave leakage, similar to the bottom section of the fly ash monitor as described in earlier technical reports. The fly ash monitor is mounted on an independent Uni-Strut stand to prevent the transfer of mechanical vibrations from the two feeders to the fly ash monitor. Below the fly ash monitor is the bottom feeder, which is connected to the fly ash monitor with a second plastic skirt that acts as a soft, flexible seal. The customized hopper is made of clear acrylic so that the flow of the fly ash could be visually inspected. The feeder tube is made of abrasion-resistant ultra-high molecular weight polyethylene (UHMW PE), which is easy to machine. A separate motor and controller drives the bottom feeder at a top speed of 470 $cm^3 min^{-1}$ (1 $ft^3 hr^{-1}$). The fly ash empties into a covered bucket to prevent fugitive dust emissions. The flow rate of the Tecweigh feeder can be adjusted to match the top speed of the bottom feeder, which is the desired flow rate of fly ash through the on-line monitor.

The most challenging aspects of the mechanical design of the fly ash monitor was developing an arrangement that allowed a packed bed of fly ash to flow in a slow, controlled manner and introducing the fly ash into the bottom feeder auger. When the fly ash was allowed to fall freely from the top feeder to the bottom feeder, there was no hang-up of fly ash. But as a packed bed, fly ash near the bottom compacted and bridged and failed to flow into the bottom feeder auger. Several modifications to the hopper design were attempted. Figure 2 is a photograph of the mechanical remedy of the problem. A second shaft was ganged off the main shaft of the bottom feeder, and narrow spindles were attached to this second shaft that agitate and stir the fly ash, preventing it from compacting. There is also dead space in the acrylic hopper, but since it is downstream of where the carbon content of the fly ash is analyzed, it is inconsequential.

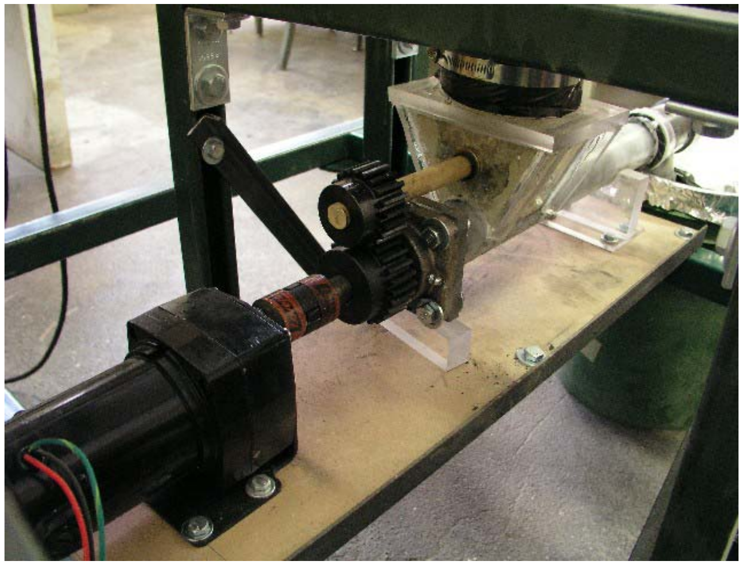

Figure 2. Bottom feeder, hopper, and agitator assembly.

Figure 3 shows the accelerometer used to measure the thermo-elastic response of the fly ash, without the lead wires connected to it. The accelerometer is a Si-Flex SF1500L Low-Noise Accelerometer from Applied MEMS, Inc, and is 24.4 mm in diameter. The accelerometer is mounted on the 51-µm thick aluminum diaphragm with a small piece of double-side Kapton tape (not shown). Lead wires will be soldered to the PC board shown that will provide the response output as well as supply the necessary DC power to run the device.

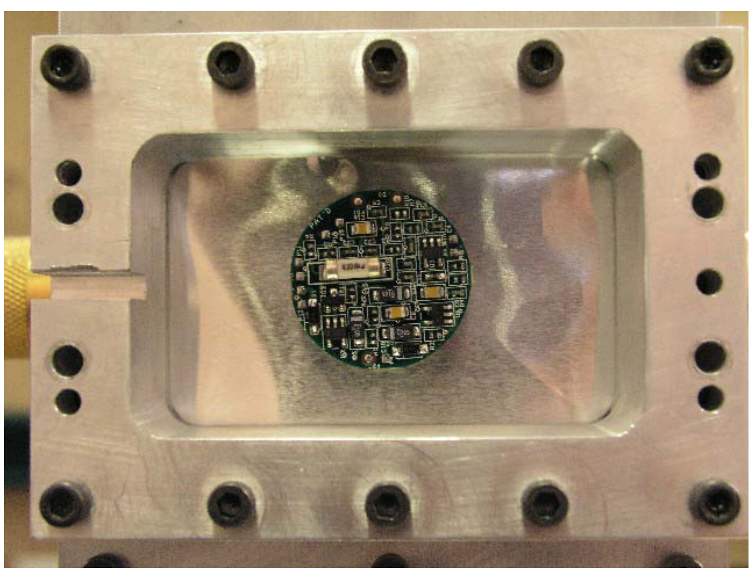

Figure 3. Accelerometer mounted on aluminum diaphragm

Construction and operation of the on-line fly ash monitor – Electrical components.

Figure 4 shows the electrical components used to generate the 1 GHz microwaves that will be used to induce a thermo-elastic response in the fly ash. The box will be mounted on the large Uni-Strut support stand of the fly ash monitor, and lead wires will be connected to both the fly ash monitor and additional data acquisition instrumentation and computer hardware (not shown).

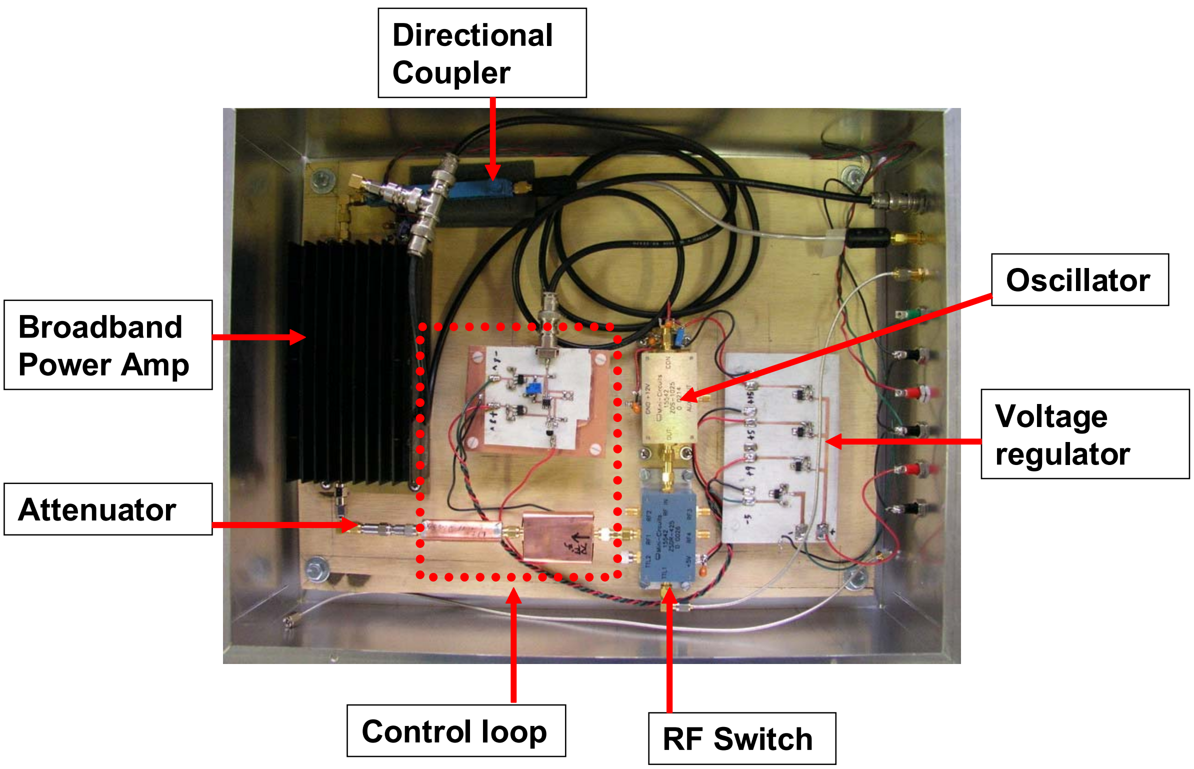

Figure 4. Electrical box containing microwave-generating equipment.

RESULTS AND DISCUSSION

RF leakage test

A Radio Frequency (RF) leakage test was conducted to confine the RF safety level defined by IEEE Standard for Safety Levels with respect to Human Exposure to Radio Frequency Electromagnetic Fields 3 kHz to 300 GHz (IEEE C95.1-1991). According to this standard, for a controlled environment, no more than 3.33 mW cm^{-2} RF power leakages allowed and for a non-controlled environment, no more than 0.66 mW cm^{-2} RF power leakages allowed. To measure the RF leakage of the fly ash monitor, 1 watt of RF power was applied into the fly ash monitor. The fly ash monitor was scanned at different spots to determine the RF leakage using a 7.6-cm monopole antenna which connected to a HP8563E spectrum analyzer. Measurements were conducted both when the monitor was empty as well as when filled with fly ash. As shown in Figure 5, the RF leakage level varies by location.

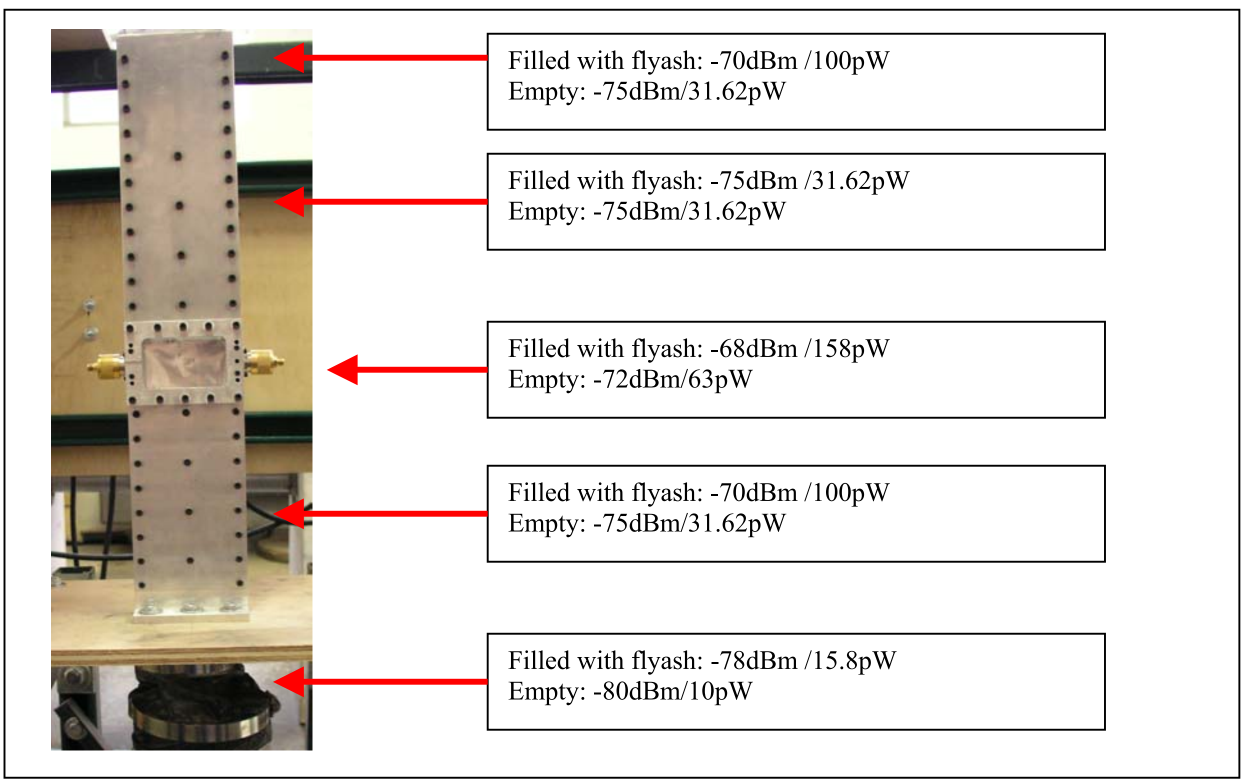

Figure 5. RF leakage test results.

To determine the RF safety level, the RF leakage power level must be expressed in terms of power density (mW cm^{-2}). Equation 1 provides the relationship of measured RF power level to power density,

$$P_{density} = \frac{P_{measured} \times 4\pi}{\lambda^2 \times G} \qquad \textbf{Equation 1}$$

where $P_{measured}$ is the measured power leakage, λ is the length of a quarter-wavelength of 1 GHz wave, and G is the gain of the monopole antenna used to measure the RF leakage, which has a value of 1.64. The largest measured power was 1.58×10^{-7} mW, which converted into power density was 1.35×10^{-9} mW cm^{-2}. This value is significantly lower than the required safety level 3.33mW/cm^2. These results reflect the robustness of fly ash monitor's design, allowing minimal RF leakage.

FUTURE WORK

The problem of making a packed-bed of fly ash to flow through the on-line fly ash monitor has been resolved, and all the necessary electrical components have been installed. The monitor has been proven to be electrical sound, limiting the amount of RF leakage to nine orders of magnitude smaller than allowed for a controlled environment. Currently, the electrical connections and power supplies necessary to operate both the microwave generating equipment as well as the accelerometer are being fine tuned, and once minor adjustments are made, the complete on-line fly ash monitor system can be tested.