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David Ray Wagner and Kevin J. Whitty

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A pulse-width modulation controlled wire-mesh heater apparatus for investigation of solid fuel pyrolysis

David Ray Wagner and Kevin J. Whitty
Department of Chemical Engineering, Institute for Clean & Secure Energy, University of Utah, Salt Lake City, Utah 84112, USA

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A novel wire mesh heater apparatus has been developed to study the devolatilization of solid fuels under pressurized conditions at well-controlled heating rates on the order of 1000 K/s. The apparatus combines direct current and pulse-width modulation with a fast-acting and high current-capacity relay to achieve operating frequencies up to 2000 Hz. This frequency allows much quicker feedback and tighter control of temperature than conventional ac-based systems that operate at 50 to 60 Hz. The present apparatus has been successfully operated at 63 bars with final temperatures of 1473 K and heating rates of 1100 K/s. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4768538]

I. INTRODUCTION

When introduced into a hot environment such as a combustor or gasifier, solid fuels undergo three distinct phases of conversion: drying, devolatilization, and char burnout. The second phase, devolatilization (also called pyrolysis), involves thermal breakdown of the fuel into gases and a carbon-rich char. For biomass, peat, and certain low-rank coals, most of the solid mass loss occurs during devolatilization. Conversion efficiency of fuels, in particular high rank coals and coke, depends strongly on characteristics of the char, which in turn depend on the devolatilization process. It is therefore important to understand how conditions during devolatilization, such as final temperature, pressure, and heating rate, affect char characteristics, and the yield and composition of gases produced. Advanced energy conversion processes such as gasification can operate at pressures approaching 100 atm, so experimental apparatuses that can evaluate devolatilization behavior under such conditions are useful.

Wire-mesh heaters, which involve the rapid heating of a fine mesh of high temperature alloy using a high amperage power source, have been used by several groups to study the devolatilization of materials under pressurized and vacuum conditions.[1–14] Typically, high-amperage power is fed to the low-conductivity grid, causing it to heat at rates in excess of 1000 K/s. When the target temperature is reached, the grid is held at a constant "soak" temperature for a specified time interval, after which the power is turned off and the grid is allowed to cool naturally. Figure 1 shows this general behavior via ramp, soak, and cooldown modes of operation.

Most of the wire-mesh heater systems that have been built have used ac power to heat the grid and a small thermocouple is attached to the grid to provide feedback to a controller, which chops the ac wave to limit power output.[1–7] Early dc power-based systems have used automotive batteries as a power supply and a crude control system involving two potentiometers to control the rate of power during heating and the soak phase.[8–12] Niksa *et al.*[13,14] developed an improved dc-heated system, which provided constant current for the heating phase followed by constant voltage to maintain the maximum temperature. However, none of the dc-based systems have had active temperature control based on mesh temperature measurements, so heating rates have been affected by system pressure and fuel characteristics.

This paper describes a wire-mesh apparatus developed at the University of Utah, which provides the same overall function as these earlier systems, but which uses a superior method of heating rate control. The system employs a high-amperage ac/dc convertor to ensure a consistent level of power and a high frequency relay and feedback control system.

II. APPARATUS

The wire-mesh heater apparatus is designed for operation at pressures as high as 70 bars, at temperatures as high as 1473 K, and at controlled heating rates of 1000 K/s. The system comprises three major components: (1) pressure vessel, (2) wire-mesh sample grid, (3) grid support system, and (4) heat control electronics.

A. Pressure vessel

The pressure vessel for the prototype system is 0.15 m diameter and 0.25 m tall, and is constructed of SCH 40 carbon steel pipe with 7.1 mm wall thickness. American Society of Mechanical Engineers (ASME) class 300 flanges on the top and bottom of the vessel make for easy assembly and maintenance of the system. The top flange has a high pressure window that allows observation of the grid during heating. High pressure Conax^{TM} fittings installed on the base of the vessel allow the feed-through of power and thermocouple wires.

B. Wire-mesh sample grid

Many high-resistance metals including stainless steels (e.g., 304, 310, 316, 321), superalloys (e.g., Incoloy 800, Monel), and pure metals (titanium, molybdenum) can be used for the wire-mesh grid. For the experiments described here, the wire-mesh grid was made of corrosion resistant 304

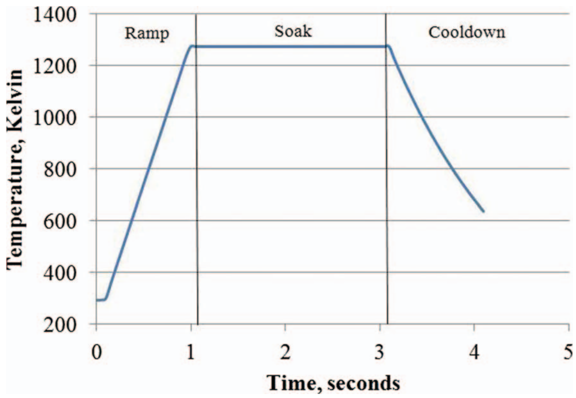

FIG. 1. Example temperature versus time curve for a heating rate of 1100 K/s and a final temperature 1273 K and a holding time of 2 s.

stainless steel with a 500 mesh size. The open area was 36.0% and the opening width between wires is 30 m. It is important that the sample be sieved to remove particles smaller than the mesh opening width. A sample of powdered fuel is placed onto a 2.5 cm by 5 cm piece of mesh that is folded in half lengthwise to form a pocket roughly 1.25 by 5 cm. The fuel sample is sandwiched between the two layers, and is centered along the 5 cm length to form a thin layer of fuel roughly 1 cm square. For each experiment, white paper is placed below the mesh in order to detect any fuel fragments that are ejected or fall through the mesh upon heating.

Temperature feedback to the control system is provided by fine (0.05 mm) R-type bare-wire thermocouple (Omega Engineering, model number P13R-002) welded directly to the grid. The fine thermocouple wires are necessary for fast response. The R-type thermocouples have a response time of approximately 0.035 s. During development, it was discovered that R-type thermocouples (as opposed to, e.g., K-type) were much more robust and less prone to breakage during heating. Figure 2 shows a photograph of the wire mesh with the R-type thermocouple junctions. The thermocouples were spot-welded to the mesh using a small dental welder.

Proper preparation of the grid and the location of the thermocouple relative to the fuel sample are important. Because fuel pyrolysis is an endothermic process, local cooling of the grid can occur as gases are evolved and pass through the mesh.

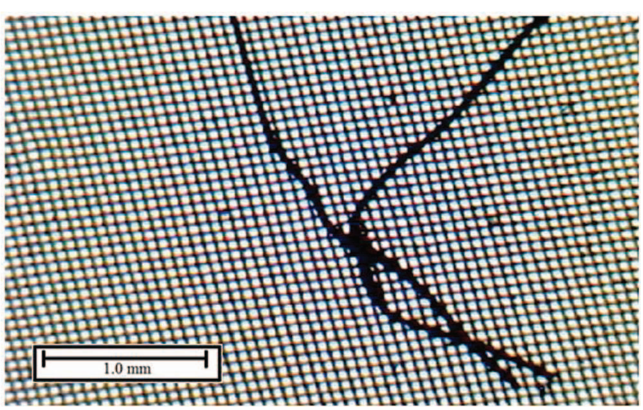

FIG. 2. Magnified photograph of the 304 SS wire-mesh and R-type thermocouple leads.

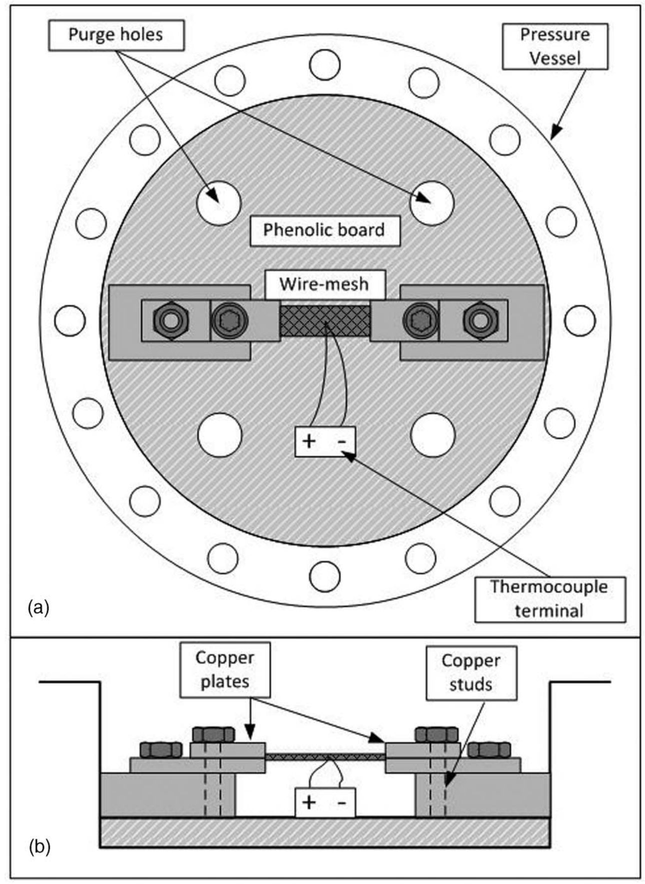

FIG. 3. Schematic of the grid and grid support system with thermocouple. (a) Top view and (b) side view.

The intention of the experiment is to subject the fuel sample to a specific heating profile. If the thermocouple is attached outside the area of the fuel sample, the temperature of the fuel will be somewhat lower than the measured temperature. It is therefore best to weld the thermocouple to the grid at a position that places it near the center of the fuel sample. Minimizing the thickness of the fuel sample also helps minimize the difference between the measured grid temperature and the fuel temperature.

C. Grid support system

The grid support system, seen in Figure 3, is affixed to a phenolic board, which serves both as an insulator and as a base for the grid supports. The phenolic board also helps reduce convective currents induced by the hot grid. The grid is supported between two copper blocks, each 6.5 mm high and 12.7 mm wide. The blocks are secured with 8.3 mm diameter copper studs that are bolted through the phenolic block. The power leads are secured to copper nuts on the underside of the phenolic block.

The block at the bottom of Figure 3 is the thermocouple terminal that connects the fine R-type thermocouple to the control electronics hardware. The phenolic board is at a fixed height, and is used to eliminate the risk of arcing to the vessel shell. Four holes were drilled in the board to allow nitrogen

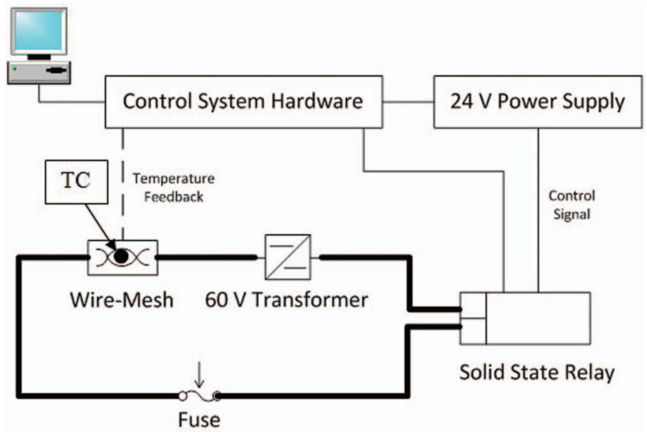

FIG. 4. Schematic of the wire-mesh heater experimental apparatus. "TC" indicates thermocouple junction placement.

to enter from the bottom and not disrupt the mesh when pressurizing.

D. Heater control electronics

A schematic of the grid heating control system is shown in Figure 4. The heat control system comprises a 60 A dc transformer powered by a standard 120 VAC outlet (Tripp-Lite model PR-60) to provide power to the grid, a high current (1000 A), fast switching (2000 Hz) solid state relay (Power-IO CDD-1V300), and a control system that adjusts power output to the grid to maintain the target temperature. The Castillejo-Dalitz-Dyson (CDD) series SSR is the only model identified that can handle the very high inrush currents and fast switching time required for precise temperature control. Temperature control is provided with the National Instruments LabVIEW-based system with thermocouple and digital output modules (National Instruments part numbers SCC-TC02 and SCC-DO01, respectively).

III. HEATER TEMPERATURE CONTROL

The heating phase of an experiment in the wire-mesh apparatus may, for example, involve heating at 3000 K/s to 1273 K, thereby completing in about 330 ms. Because devolatilization behavior is sensitive to heating rate, it is important to maintain a linear temperature profile during this phase. As the sample devolatilizes, it undergoes endothermic decomposition reactions that release gas that passes through the grid, so dynamically controlling the rising temperature of the grid can be challenging. Ac-based systems, which operate at line frequency (50–60 Hz), operate by "chopping" the sine wave during a given cycle. The theoretical maximum number of control cycles that can be achieved is thus 50 to 60 per second. For an experiment with a temperature rise of 1000 K at 3000 K/s, this offers just 17–20 feedback cycles with roughly 55° of temperature rise between cycles. This makes the accurate control of this dynamic system, particularly PI or proportional-integral-derivative (PID) control, very challenging. The system described here overcomes that by using dc power and a very fast solid state relay (SSR, rated to 2000 Hz), combined with a National Instruments LabVIEW-controlled pulse-width modulation (PWM) scheme, for power control. For the experiment described above, the SSR-based system at 2000 Hz would offer approximately 670 temperature control cycles. With direct current, a consistent signal can be delivered with grid temperatures being taken before the circuit is switched to the "on" position. The temperature of the grid is measured during the "off" position in order to remove any interference from other electronic signals. This is superior to ac-based systems, which attempt to measure temperature when the power voltage sine wave equals 0 V, and which in some cases must average two temperature measurements to compensate for noise associated with a phase-angle shift.[4] Even if there is residual electronic noise on the grid, the National Instruments thermocouple module (SCC-TC02) is protected against voltage interference up to 14 V. Also, by using direct current, the presence of wave-chopping or segmentation required by ac-based systems is removed. The overall result is a smoother, more consistent, and more tightly controlled heating profile that is independent of system pressure, gas atmosphere, or fuel characteristics.

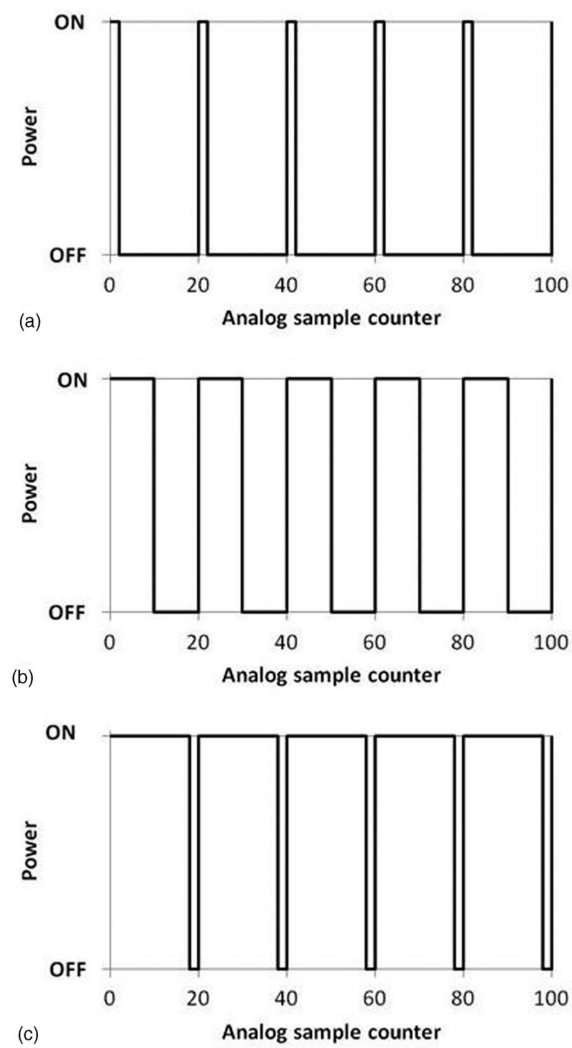

FIG. 5. Simulated power versus PWM sample frequency for (a) 10% duty cycle, (b) 50%, and (c) 90%.

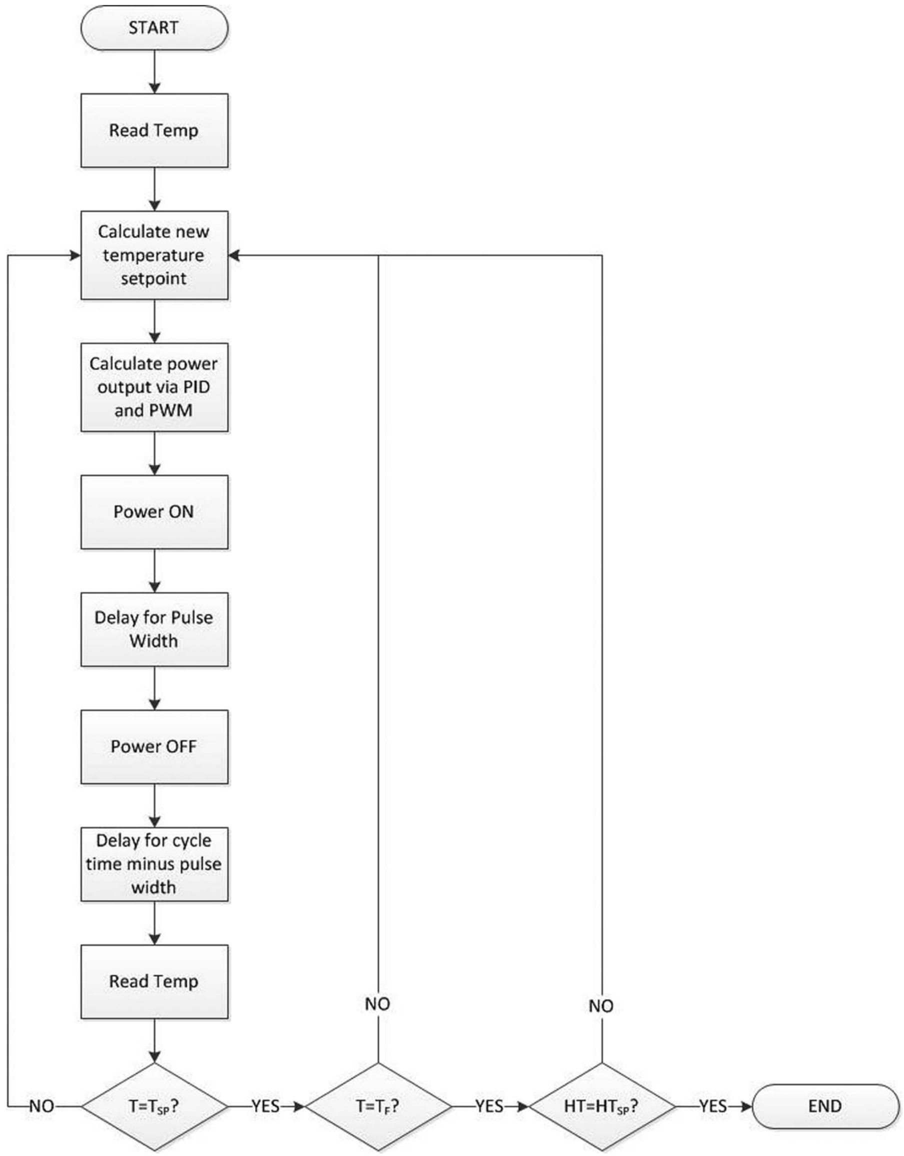

FIG. 6. LabVIEW programming flowchart. Subscripts "SP" and "F" denote setpoint and final values, respectively. HT denotes hold time.

The PWM frequency is calculated within LabVIEW by dividing the counter frequency (or loop rate of the LabVIEW data acquisition chip, which operates at a higher frequency than the SSR) by a constant simply called the divider, which sets the sampling frequency. The divider allows the two major loops of the LabVIEW programming to synchronize the temperature measurement and duty cycle, or power being supplied to the grid. The PID settings are calculated for each iteration and sent to the digital output loop via the duty cycle. Figure 5 demonstrates the use of PWM frequencies and duty cycle with power delivered.

The LabVIEW programming is best represented by Figure 6, a flowchart of all major programming decisions and processes.

After beginning the program, the temperature is read and a setpoint is calculated based on the value of the reading. The required power output is also calculated and applied via PI or PID settings, in conjunction with desired pulse-width modulation settings. Upon the completion of this loop, the temperature is read and based on the operator's criteria, will continue heating, soaking at the final temperature, or end the program. If the temperature is at the calculated setpoint, the final temperature, and has soaked for the desired hold time, the program will end and power is cut to the system.

IV. EXPERIMENTAL PROCEDURE

The operation procedure for the University of Utah's wire-mesh heater is similar to those of other studies. A fine wire mesh folded around a sample of solid fuel is clamped between two conducting plates or jaws and current is run through at a controlled rate to achieve a desired temperature profile. The apparatus uses a type R thermocouple (platinum/rhodium) to accommodate high temperatures. The thermocouple is welded to the mesh, ensuring a constant and local temperature reading. The fuel is placed on the mesh-thermocouple junction so that the measurement is assured to be the fuel temperature and not just the temperature of the metal. All fuel is sieved to a particle diameter range of 38 to 75 m, which is larger than the opening in the wire mesh, but still small to promote good heat transfer to the fuel particles. For pressurized operation, the vessel is sealed and nitrogen is run through the system to ensure no oxygen is present. The vessel is then slowly pressurized at about 6 bars/min to the desired pressure and allowed to rest until the thermocouple measurement fluctuations stabilize. Using the LabVIEW interface, desired final temperatures, hold times, and heating rates are specified. After a test is complete, the pressure is slowly released via a needle valve, the grid containing the sample is carefully released and removed from the apparatus, and the char and volatile yields are calculated.

V. SUMMARY

The University of Utah has successfully built and operated a dc-powered grid heater with the novel implementations of kilohertz pulse-width modulation and high-amperage electronics in order to achieve dynamically-controlled heating rates in excess of 10^3 K/s. High pressures and final grid temperatures have also been achieved and future test campaigns include coal and petroleum coke pyrolysis in order to study devolatilization and subsequent char burnout.

[1]R. C. Messenbock, D. R. Dugwell, and R. Kandiyoti, Energy Fuels **13**, 122–129 (1999).
[2]A. J. Guell and R. Kandiyoti, Energy Fuels **7**(6), 943–52 (1993).
[3]D. Peralta, N. Paterson, D. Dugwell, and R. Kandiyoti, Energy Fuels **19**, 532–7 (2005).
[4]J. R. Gibbins, R. A. V. King, R. J. Wood, and R. Kandiyoti, Rev. Sci. Instrum. **60**(6), 1129–39 (1989).
[5]C. Sathe, Y. Pang, and C.-Z. Li, Energy Fuels **13**, 748–55 (1999).
[6]C. Sathe, J.-I. Hayashi, and C.-Z. Li, Fuel **81**, 1171–8 (2002).
[7]C. Zeng *et al.*, Rev. Sci. Instrum. **79**, 084102-1–5 (2008).
[8]E. M. Suuberg, W. A. Peters, and J. B. Howard, in *Proceedings of the 17th Symposium (International) on Combustion* (The Combustion Institute, Pittsburgh, PA, 1978), pp. 117–30.
[9]P. E. Unger and E. M. Suuberg, in *Proceedings of the 18th Symposium (International) on Combustion* (The Combustion Institute, Pittsburgh, PA, 1981), pp. 1203–11.
[10]D. B. Anthony, J. B. Howard, H. C. Hottel, and H. P. Meissner, in *Proceedings of the 15th Symposium (International) on Combustion* (The Combustion Institute, Pittsburgh, PA, 1975), pp. 1303–17.
[11]D. B. Anthony, J. B. Howard, H. P. Messner, and H. C. Hottel, Rev. Sci. Instrum. **45**(8), 992–5 (1974).
[12]E. M. Suuberg, W. A. Peters, and J. B. Howard, in *Thermal Hydrocarbon Chemistry*, edited by A. G. Oblad, H. G. Davis, and T. R. Eddinger (American Chemical Society, 1979), pp. 239–57.
[13]S. J. Niksa, W. B. Russel, and D. A. Saville, Fuel **61**, 1207–12 (1982).
[14]S. Niksa, W. B. Russel, and D. A. Saville, in *Proceedings of the 19th Symposium (International) on Combustion* (The Combustion Institute, Pittsburgh, PA, 1982), pp. 1151–57.