EFFECT OF HEATING RATE ON THE THERMODYNAMIC PROPERTIES OF
PULVERIZED COAL

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ABSTRACT

This semi-annual technical progress report describes work performed under DOE Grant No. DE-FG22-96PC96224 during the period March 24, 1998 to September 23, 1998 which covers the fourth six months of the project. Existing laser heating set-up at the Single Particle Laboratory, Federal Energy Technology Center, Morgantown, WV would work only in the range of 10^4 to 10^5 K/s. During this reporting period, appropriate changes were made to the laser heating system to heat particles in the range of 10^4 to 10^7 K/s. Also, calibration for all the components of the electrodynamic balance measurement system including single-color pyrometer and heating laser was successfully completed. Following the calibration, a large number of single coal particles were caught in the electrodynamic balance and their volume, external surface area, mass, and density were measured. The same single particles were then heated bidirectionally with a pulsed (10 ms pulse width) Nd:YAG laser beams of equal intensity. The temporal power variation in the laser pulse was monitored for use in the heat transfer analysis by an ultra-fast fiber optic uv light transmitter included in the beam path and coupled to a silicon photodiode. Measurements of changes in particle size that accompanied rapid heating was made by means of the high-speed diode array imaging system discussed in our previous reports. Dynamics of volatile evolution and particle swelling were recorded using well established time-resolved high-speed cinematography. Measurements of the radiant emissive power from the heated and cooled (when the laser is turned off) particles was made using the single-color pyrometer. The above experiments are being repeated for a significant number of coal particles for a number of heating rates in between 10^4 - 10^7 K/s at FETC, Morgantown. Shipment of the donated heated grid system components from our industrial partner, United Technologies Research Center (UTRC), CT to CAU was complete during this reporting period. Testing of the heated grid system components at CAU is also in progress.

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EXECUTIVE SUMMARY

In this semi-annual report, the work performed under DOE Grant No. DE-FG22-96PC96224 during the period March 24, 1998 to September 23, 1998 is described and the major accomplishments are highlighted summarizing the most important research results.

In all major coal conversion processes, coal undergoes a devolatilization stage while it is heated to the reaction temperature. The recent experimental studies of devolatilization of pulverized coal at rapid heating rates representative of coal combustors have greatly improved our general understanding of this process. But the heat transfer analysis with commonly-applied thermal properties developed from slow heating rate experiments did not predict either the early heating or the latter stages of heating. Knowledge of the role of heating rate on coal thermal properties is essential to progress in advanced coal utilization technology.

The objectives of this proposal are to understand the effect of heating rate on thermal properties of pulverized coal particles. The specific objectives are to subject coal particles into a broad range of heating rates, measure temperature histories, and develop thermal property (heat capacity and thermal conductivity) data that predict the measured temperature histories.

Experiments and modeling are being carried out to meet the project objectives. The successful accomplishment of the above goals will enhance our understanding of coal thermal properties and hence progress towards advanced combustion modeling.

During this reporting period, calibration for all the components of the electrodynamic balance measurement system including single-color pyrometer and heating laser at the Single Particle Laboratory, Federal Energy Technology Center, Morgantown, WV was successfully completed. The original set-up of the heating laser would heat particles only in the range of 10^4 to 10^5 K/s. Prior to calibration, power attenuator and the charge voltage of the heating laser system were carefully adjusted and the beam path reconfigured to heat particles in the range of 10^4 to 10^7 K/s. Following the calibration, a large number of single coal particles were caught in the electrodynamic balance and their volume, external surface area, mass, and density were measured. The same single particles were then heated bidirectionally with the heating laser and particle surface temperatures were measured using the single-color pyrometer. The temporal power variation in the laser pulse was monitored for use in the heat transfer analysis by an ultra-fast fiber optic uv light transmitter. Measurements of changes in particle size that accompanied rapid heating was made by means of the high-speed diode array imaging system. Dynamics of volatile evolution and particle swelling were recorded using time-resolved high-speed cinematography. The above experiments are being repeated at FETC, Morgantown for a significant number of coal particles with heating rates in between 10^4 - 10^7 K/s. Shipment of the donated heated grid system components from UTRC to CAU was complete during this reporting period. Inspection and testing of the heated grid system components at CAU are also in progress.

INTRODUCTION

This semi-annual technical progress report describes work performed under DOE Grant No. DE-FG22-96PC96224 during the period March 24, 1998 to September 23, 1998 which covers the fourth six months of the project.

In all major coal conversion processes, coal undergoes a devolatilization stage while it is heated to the reaction temperature. Recent experimental studies of devolatilization of pulverized coal at rapid heating rates representative of coal combustors have greatly improved our general understanding of this process [1-18]. But the heat transfer analysis with commonly-applied thermal properties developed from slow heating rate experiments did not predict either the early heating or the latter stages of heating [1-3,18-19]. Design of coal combustion and conversion processes require knowledge of thermal properties to construct an energy balance. It is accepted that there are uncertainties in the heat capacity of coal especially for the high heating rate studies [2,6]. It is also accepted that the large thermal gradients within the particle (due to thermal conductivity of coal) make prediction of the temperature difficult during the early heating in these studies [6]. However, there has been no independent study conducted to investigate the effect of heating rate on the thermal properties of coal particles. Knowledge of the role of heating rate on coal thermal properties is essential to progress in advanced coal utilization technology.

The objectives of this proposal are to understand the effect of heating rate on thermal properties of pulverized coal particles. The specific objectives are:

- 1) Subject coal particles into a broad range of heating rates and extract heat capacity information for high heating rate applications.
- 2) Also develop thermal conductivity information for coal particles subjected to rapid heating rates representative of coal combustors.

Experiments and modeling are being carried out to meet the project objectives. The successful accomplishment of the above goals will provide better understanding of coal thermal properties in high heating rate applications and hence improved combustion modeling.

PROGRESS TO DATE

Literature articles [1-45] were reviewed to understand the effect of heating rate on various parameters of a coal particle. The role of heating rate on the onset of volatile evolution, volatile yield, product composition to a lesser extent, coal type and particle size were found to be well established. As heating becomes more rapid, the onset of devolatilization shifts to much smaller time scales and to much higher surface temperatures [2,18-19]. However, the role of heating rate on coal thermal properties was not found to be well understood. Previous results clearly demonstrated that particle temperature-dependent thermal property assumptions routinely applied in coal combustion models result in large errors (up to 100 percent) in calculated temperature histories [2,18-19].

Remote access from CAU to the VAX/VMS system at FETC/Morgantown was established through telnet. Several modifications to the existing Single Particle Heat Transfer code were made that include option for various input and/or combinations of input for thermal properties such as constant, temperature-dependent, heating rate dependent, and time dependent values. Many sensitivity analyzes were employed to evaluate and quantify the impact of several heat transfer parameters for coal such as thermal properties and heat transfer coefficient, geometry related properties such as shape, mass, and density, and chemical properties such as devolatilization kinetic coefficients on rapid heating. This work improved the model performance of the present work, and also aided in several publications [46-50].

Approval for physical access to the Single Particle Laboratory at FETC/Morgantown from Morgantown facility was obtained. This required completion of several laboratory safety courses by CAU researchers including the PI at the Morgantown site.

Several polystyrene spheres were caught in the electrodynamic balance system at FETC/Morgantown and the operation of the associated system components such as video-based imaging systems, diode-array imaging system, dc and ac power supply, particle position control, and GE tungsten strip lamp & lens systems for pyrometer were tested and found to be performing well. Completed calibration of several components of the balance measurement system including imaging systems and particle position control system. Also completed was the alignment and calibration of the heating laser to heat coal particles, and the single-color pyrometer to measure particle temperature histories.

Approvals from FETC/Pittsburgh, CAU, and UTRC for performing the heated grid work at Clark Atlanta University (CAU), GA, that was originally planned at United Technologies Research Center (UTRC), CT, were obtained. More recently, donation agreement for the heated grid measurement system from UTRC was obtained and the shipment of the grid components from UTRC to CAU was complete. Purchase of several instrumentation that were not available in the package from UTRC that include power supply, data acquisition interface, and spot welder was made by CAU.

WORK PERFORMED DURING THIS PERIOD

Existing laser heating set-up at the Single Particle Laboratory, Federal Energy Technology Center, Morgantown, WV would work only in the range of 10^4 to 10^5 K/s. During this reporting period, appropriate changes were made to heat particles in the range of 10^4 to 10^7 K/s. For this, power attenuator and the charge voltage of the heating laser system were carefully adjusted, beam path reconfigured and aligned, and the laser power characterized to obtain optimum spatial and temporal distribution.

Calibration for all the components of the electrodynamic balance measurement system including single-color pyrometer and heating laser was successfully completed. Following the calibration, a few coal particles were injected into the balance and by application of ac and dc potentials to the ring and endcap electrodes, a single particle that had a higher charge-to-mass ratio

Table 1. Raw Data for the EDB Experiments March 24 - September 23, 1998

		Rotation	Rotation	Rotation	Rotation	Laser	Side	Side	Side	Top	Top	Top
Part#	Cd/m	Area	Volume	Dp area	Dp vol	Power	Dp area	Dp #line	Dp #width	Dp area	Dp #line	Dp#width
1	49	26841	326542	93	85	0.63	85	84.8	88.4	77	93.8	70.8
2	52	33015	449444	103	95	0.65	74	115.3	57.4	82	65.9	113.2
3	31	34713	537058	105	101	0.63	95	113.6	84.5	91	77.8	103.8
4	32	36345	543636	108	101	0.64	106	100.1	112.3	107	113.6	99
5	22.5	47664	805956	123	115	0.64	123	164.5	93.9	99	105.6	101.5
6	80	75865	1533570	155	143	0.66	144	170.1	142	130	126.9	151.5
7	28	41374	691213	115	110	0.65	118	114.2	139	103	134.4	75.8
8	35	31006	408401	99	92	0.65	102	159.4	80.4	82	79.7	91.6
9	27	49500	798314	126	115	0.65	100	131	82.6	105	84.9	153
10	32	34096	518157	104	100	0.66	105	114.9	91.4	81	78.4	95.7
11	36	34933	515043	105	99	0.33	110	100.7	125.9	101	115.4	94.6
12	29	40315	660464	113	108	0.33	125	135.4	138.2	96	134	80
13	34	33469	464040	103	96	0.4	101	94.6	116.1	96	115.3	90.2
14	27	62815	970536	141	123	0.4	124	104.7	165.9	120	162.3	94.4
15	30	51816	828580	129	117	0.32	109	144.2	88.9	107	93.4	122.9

was confined at the null position of the balance. Following the approach of Maloney et al. [21-23], the particle volume, external surface area, mass, and density were measured. The same particle was then heated bidirectionally with a pulsed (10 ms pulse width) Nd:YAG laser beams of equal intensity. Using the approach of Sampath [18-19], the temporal power variation in the laser pulse was monitored for use in the heat transfer analysis by an ultra-fast fiber optic uv light transmitter included in the beam path and coupled to a silicon photodiode. Measurements of changes in particle size that accompanied rapid heating was made by means of the high-speed diode array imaging system. Dynamics of volatile evolution and particle swelling was recorded using well established [2,5,18] time-resolved high-speed cinematography. Measurements of the radiant emissive power from the heated and cooled (when the laser was turned off) particles was made using the single-color pyrometer. Particle experimental temperatures was calculated from the measurements of particle size and radiant emissive power by applying the Wein approximation to Plank's law. The above experiments are being repeated for a significant number of coal particles for various heating rates in between 10^4 - 10^7 K/s. Raw size and intensity data for 15 coal particles tested during this reporting period are presented in Table 1. Further experimentation and data reduction, and numerical analysis for the effect of thermal properties on the temperature histories are in progress.

Dr. Sampath, PI of this project, was at FETC/Morgantown in several visits during this reporting period. He was involved in the alignment and setting up of the pyrometry system. Dr. Esmail Monazam who has coauthored with the PI in a number of publications in the subject matter is working as a part-time research associate in this project and is stationed at FETC/Morgantown. Dr. Monazam is involved in the experimental activities discussed above.

Donation agreement for several components of the heated grid measurement system from UTRC was obtained during this reporting period and the shipment of the donated components from UTRC to CAU was complete. Purchase of several instrumentation that were not available in the donation package from UTRC that include power supply, data acquisition interface, and spot welder

was made by CAU. Inspection and testing of the grid components, and their installation at CAU, and the modification and testing of the heated grid numerical code at CAU are in progress.

Joie C. Taylor, an undergraduate student in Engineering, was partially supported and trained in the subject matter.

Several theoretical analyses were conducted to improve the model performance of the present work and the results were compared with data available from our previous studies. These activities resulted in one journal publication [47], three conference presentations [46,49-50], and one symposium presentation [48] during this reporting period.

OUTCOMES TO DATE

1. Sampath, R., Monazam, E. R., Maloney, D. J., and Zondlo, J. W., Development of Improved Coal Combustion Modeling: Analysis of Coal Particle Irregularity and Thermal Properties on Temperature Predictions, Fifth Annual HBCU conference organized by FETC/DOE at Southern University and A&M College, LA, March 1997.
2. Sampath, R., Maloney, D. J., and Monazam, E. R., Effect of Heating Rate on the Thermodynamic Properties of Pulverized Coal, Contractors Review Meeting, Fifth Annual HBCU conference organized by FETC/DOE at Southern University and A&M College, LA, March 1997.
3. Taylor, J. C., Sampath, R., Maloney, D. J., Zondlo, J. W., and Monazam, E. R., Transport Phenomena of Irregularly-Shaped Solid Particles in an Electrodynamic Balance, Poster Paper, Fifth Annual HBCU conference organized by FETC/DOE at Southern University and A&M College, LA, March 1997.
4. Sampath, R., Maloney, D. J., Zondlo, J. W., and Monazam, E. R., Temperature Histories for Single Coal Particles Prior to Devolatilization, Central States Technical Meeting, Combustion Institute, April 1997, Point Clear, AL.
5. Taylor, J. C., Sampath, R., and Maloney, D. J., Characterization of Small Single Particles in an Electrodynamic Balance, Annual Student Scientific Research Symposium, April 15, 1997, Clark Atlanta University, Atlanta, GA.
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7. Maloney, D. J., Sampath, R., and Zondlo, J. W., Heat Capacity and Thermal Conductivity Considerations for Coal Particles During the Early Stages of Rapid Heating, Combustion and Flame 116:94-104 (1999).

8. Sampath, R., Maloney, D. J., and Zondlo, J. W., Evaluation of Thermophysical and Thermochemical Heat Requirements for Coals at Combustion Level Heat Fluxes, 27th International Symposium on Combustion, August 2-7, 1998, Boulder, CO.
9. Sampath, R., Maloney, D. J., and Proscia, W., Thermal Property Data for Coal Particles for Use in Rapid Devolatilization Models, Technology Transfer Session, Historically Black Colleges/Universities and Other Minority Institutions Annual Symposium, April 28-29, 1998, Ocean City, MD.
10. Taylor, J., Sampath, R., Maloney, D. J., and Proscia, W., Rapid Devolatilization Studies for Coal Particles in an Electrodynamic Balance and in a Heated Grid Reactor, Technology Transfer Session, Historically Black Colleges/Universities and Other Minority Institutions Annual Symposium, April 28-29, 1998, Ocean City, MD.
11. Sampath, R., Maloney, D. J., and Zondlo, J. W., Measurements of Surface Area and Volume for Irregularly-Shaped Coal Particles, Central States Technical Meeting, Combustion Institute, 31 May - 2 June, 1998, Lexington, KY.

PLANS FOR THE NEXT REPORTING PERIOD

In the near future, high-heating rate experiments will be completed at FETC, Morgantown, and heated grid work will be carried out at CAU. Following these activities, data reduction and numerical analyses will be made and the effect of heating rates on coal thermal properties evaluated.

SUMMARY AND CONCLUSIONS

The project is progressing well. Calibration activities for various instruments of the EDB measurement system, Single Particle Laboratory, FETC, Morgantown, were completed. Donation agreement for the donation of several components of the heated-grid system from UTRC, our industrial collaborator in this project, was obtained. Shipment of donated components from UTRC to CAU was complete. Calibration of the single-color pyrometer, and heating laser at the Single Particle Laboratory, FETC, Morgantown was complete. Temperature measurements on 15 coal particles subjected to very high heating rates were made during this reporting period and further experimentation to about 30 particles is in progress.

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