ABSTRACT

The purpose of this project was to examine the feasibility of laser-based and optical diagnostics in reactive flows of relevance to coal engineering. These diagnostics have been used with significant success in order to investigate the fundamentals of the energy conversion of gaseous and liquid fuels. The challenge for application in coal lies in that the flows are typically optically thick, i.e. non-transparent. In order to address this challenge, two burners were established that could be inserted in the laser-diagnostic facility of the PI’s laboratory in the University of Illinois at Urbana-Champaign. Based on their principle of operation, they were termed “diffusive” and “counterflow” burner. The “diffusive” burner was used in order to study propagation into gradually leaner mixtures and the “counterflow” burner was used in order to study propagation into near-stoichiometric and rich mixtures. In both cases the speed of flame propagation was measured and was compared with the flame speed that corresponded to the local composition of the mixture. This process showed that flame propagation cannot be considered as a “quasi-homogeneous” phenomenon, where the flame propagates based on the local properties of the mixture. Instead, the combustion scenario depends heavily on the “history” of flame propagation. Back-supported by vigorous combustion in some locations, the flame can penetrate subsequent locations that are beyond the flammability limits. This is an important finding in the context of safety, since it shows that staying outside the flammability limits cannot guarantee safe combustor operation. Additionally, it was shown that velocity measurements can be acquired in coal-laden environments using Particle Image Velocimetry. The existence of particles in the coal-laden streams facilitates the application of the technique which requires condensed-phase seeds in the flow field. However, it also raises the interesting question whether both gaseous phase and coal-particle velocities can be measured, possibly with the insertion of fine particles in the stream. Particle size measurements were also attempted using a Fraunhofer-diffraction based techniques but were not successful at this stage, probably because of inadequate power of the employed laser.
EXECUTIVE SUMMARY

Optical and laser-based diagnostics is a technique that has so-far been used in conjunction with reactive flow and power-conversion processes of gaseous and liquid fuels. This is due to a significant degree of the need for clean, optically accessible environments in order for the diagnostics to be developed. Indeed, it has repeatedly been the case that combustion configurations are chosen with the sole criterion that they are “easy” in order for a new diagnostic to be tested. Frequently e.g. unrealistic dilution of the reactant streams is used in order to diminish soot and therefore facilitate the application the diagnostic.

The research conducted in this exploratory study is inspired by the inverse mentality: Can the diagnostic technique be applied in a practically relevant combustion application without a priori requirements regarding “cleanliness” of the experiment and its potential then evaluated. Coal, being used for the production of almost 50% of the power in the nation is a natural choice of such an environment, which is very relevant in terms of practice, but still optically thick, i.e. non-transparent.

The approach that was followed in order to address this challenge comprised of two parts: First, experimental burners were devised that were adapted in the laser-diagnostic facility of the Combustion Physics laboratory of the University of Illinois at Urbana-Champaign. Second, a series of diagnostics were tested in these burners in order to establish their feasibility.

In particular the following two burner designs were established:

a. “Diffusive” burner. This was an extrapolation of our previous work with natural gas. It is a burner that establishes compositional stratification through diffusion of the components of the fuel mixture into a stream of pure air. Because of the way the burner is constructed, flame propagation in this burner can only occur towards gradually leaner mixtures. It is reminded that this is a significant drawback since propagation into lean and into rich mixtures is not symmetric: Oxidizer excess in lean flames acts pretty much as an inert, which is not the case for the excess fuel in a rich flame.

b. Counterflow burner. In order to achieve better control of the compositional stratification as well as flame propagation in near-stoichiometric and rich mixtures, we established a new burner design in which compositional stratification is achieved through a counterflow of two streams of different composition. This burner allowed for the establishment of almost linear concentration gradients. In order to facilitate ignition, the fuel stream contained natural gas. Natural gas and coal particles were assumed to diffuse not too differently from each other and fuel equivalence ratio was measured using laser induced fluorescence.

Experiments in these two burners yielded findings in the following areas:

- Flame propagation in compositionally stratified fuel streams. High-speed visualization of the flames in conjunction with equivalence ratio measurements led to the conclusion that combustion in a medium of varying composition cannot be treated in a
quasi-homogeneous way. In particular, it was shown that in most cases flames that propagate from an almost stoichiometric into gradually leaner or richer mixtures do not travel with the flame speed corresponding to the local equivalence ratio but faster. This is potentially important for safety design because it shows that flames can propagate into presumably non-flammable mixtures. It was actually possible to ignite and burn in stratified media that were below the flammability limit in almost all of their extent. The difference between actual flame speed and quasi-homogeneous one is particularly intense in the case of rich mixtures, where differences by a factor on the order of two were recorded. In the lean cases, the corresponding difference were 50% at maximum.

- **Particle Image Velocimetry in coal-laden streams**: It was established that Particle Image Velocimetry can be used as a tool to measure velocities in coal-laden streams. In the experimental burners, speeds on the order of 1 m/s were measured for the particles, but a process has been established that can in principle be used in order to measure a wide range of speeds. An interesting possibility that emerged during this feasibility study but was not thoroughly investigated was the one of measuring both coal particle and gas phase velocity. This can be achieved by inserting fine particles in the flow (e.g. alumina) that can track the gaseous motion accurately.

- **Particle size measurements**: Measurements of particle size were attempted using a Fraunhoffer-diffusion-based instrument (Malvern), following the processes that we had used for liquid fuel droplets. These measurements were not successful. The laser beam was attenuated by the non-transparent particles and no measurement was possible. In an effort to overcome this hurdle, a new instrument was acquired (not with ICCI funds) which will be used in order to pursue similar measurements in the future.
OBJECTIVES

An exploratory study was performed with the following two main objectives:

- To establish well controlled burners into which it would be possible to establish the feasibility of the laser-diagnostics that have been widely used for gaseous and liquid fuels for coal-laden streams.
- To examine an array of laser-based and optical diagnostics and determine whether it is possible to use them in order to extract information that is useful for the design of coal-based systems.

In order to achieve these objectives, the following tasks were pursued:

1. Introduction of coal particles to a “diffusive” burner that had been used in the PI’s group for natural gas combustion studies.
2. Establishment of a counterflow burner that offered a better control of the coal-laden streams.
3. Study of the combustion in compositionally stratified mixtures. Comparison with the “quasi-homogeneous” case where the flame can be assumed to propagate with the flame corresponding to the local equivalence ratio.
4. Investigation of the possibility of Particle Image Velocimetry (PIV) measurements of velocity in coal-laden streams.
5. Investigation of the possibility of laser-based particle size measurements in coal-laden streams.

INTRODUCTION AND BACKGROUND

The purpose of the performed work was to investigate the introduction of laser diagnostics to coal-related problems. A typical laser diagnostics apparatus is shown schematically in Figure 1. It basically comprises of three components:

a. **Appropriate lasers that are used as sources of excitation.** The use of lasers a diagnostic tool for energy conversion processes is by now well established [1]. In engineering practice in general and in our work in particular [2-7], lasers like the Nd-YAG and the dye laser that are available at the Combustion Physics laboratory at UIUC have been used in order to study combustion of gaseous and liquid fuels. Exploration of these capabilities for coal was pursued through appropriate coal burners described in the experimental procedures section of this report.

b. **The combustion test section.** This can

![Figure 1. Typical laser diagnostics apparatus.](image-url)
include a wide variety of devices, both in terms of practical injectors, combustors, and engines [5-7] as well as optically accessible combustors that have been modified so that laser probing is facilitated [2-4]. The laser beam is guided in the combustion test section and either causes an appropriately designed excitation of the gases in the test section or is scattered by the coal particles.

c. Data acquisition equipment. This captures the “response” of the test section to laser excitation and translates this to quantitative information about the combustion process with a particular emphasis on measurements of emissions [8], as well as particle size and temperature [9] and velocity measurements.

The advent of lasers has equipped power engineers not only with more accurate measurements but with completely new capabilities that include spatially resolved, instantaneous measurements acquired at high rates. This methodology allows for the combustion process be “frozen” and/or probed at high frequencies. The general advantages of laser diagnostics can be summarized as follows:

- Provided that optical access is available, laser-based techniques are non-intrusive and performed in-situ which eliminates the limitations of e.g. “sample-and-analyze” techniques.
- Probe volumes have characteristic length scales on the order of 10-1000 μm (depending on the particular selection of laser and excitation optics) and laser pulses used for excitation are on the order of 10⁻⁹ to 10⁻⁶ s long (depending on the particular laser), which offers the capability for enhanced temporal and spatial resolution.
- If configured appropriately, laser diagnostics can yield measurements in several dimensions (line, planar or 3D), which are very appropriate for collaborative approaches with advanced computations.

Much of these techniques have been successful for the study of gaseous and liquid fuels. It is reminded that these fuels are practically transparent. The purpose of the work reported here was to investigate the feasibility of these methods in coal burners. The coal particles are clearly non-transparent and this generates an optically thick environment.

EXPERIMENTAL PROCEDURES

A major task that was accomplished was the establishment of optically accessible burners in which flame propagation in compositionally stratified mixtures was studied with several laser-based and optical techniques. The two burner designs that were employed as well as the measurement apparatus are described in this section:

a. “Diffusive” burner: At an initial stage, the burner of Figure 2 was used as an extrapolation of our work in gaseous fuels. In order to facilitate ignition, air-methane mixtures were used in order to entrain Illinois Coal Particles provided by the Argonne National Laboratory in the screen shown in Figure 2. A mixture of constant equivalence ratio equal to $\phi \approx 1.0$ flowed continuously over the top of the chamber, where the stratification was established and the mixture was left to diffuse into the chamber through a series of staggered wire grids. This diffusion was counter-balanced by the slow
convection of pure air. In this manner a convective diffusive balance is established in the chamber which is described by the mass balance:

$$\rho D \frac{d^2 Y}{dx^2} - \rho v \frac{dY}{dx} = 0 \tag{1}$$

where $v$ the air stream velocity and $y$ the spatial location in the chamber. Since continuity guarantees that $\rho v$=const, eq. (1) accepts solutions of the form:

$$Y = A + B \cdot \exp(v \cdot x/D) \tag{2}$$

where the constants $A,B$ are determined by the boundary conditions. In this manner, stratification was achieved in a layer of a characteristic thickness on the order of $D/v$. The gradient of $Y$ (or, equivalently, $\phi$) in the cold mixture varied as a function of $x$ and could be controlled by varying $v$. The air “breeze” $v$ was on the order of about 1 cm/min, which yielded thicknesses of stratified zones on the order of several cm.

To experimentally measure the compositional stratification in the cold mixture, we doped methane with acetone in a bubbler and measured acetone PLIF. The fluorescence was excited at 266 nm with the 4th harmonic of a Nd-YAG laser and the signal was collected with an Andor iStar ICCD camera and a 25 mm, f# 4.5 quartz lens of Uka Optics. A Schott WG-305 and Hoya U-360 long pass filters were used for stray light rejection.

![Figure 2. Optically accessible test chamber for stratified combustion.](image)

The flame was ignited in the stratified mixture with a spark plug and propagated downwards to avoid Rayleigh-Taylor instabilities. An additional screen (indicated as “screen B” in Figure 4) was placed immediately above the spark plug to avoid upward propagation of the flame. The cross-section of the chamber we used was 20 x 20 x 100 mm and the flame propagated through a total length of about 9 cm. The chamber was equipped with three quartz side-windows for optical access. A valve on the top of the chamber was opened right before ignition to avoid pressure build-up and effects of gas-expansion during the propagation. Pressure measurements with appropriately coated Kister 211B4 pressure transducers confirmed that the propagation was isobaric.
Flame speed was measured by monitoring the propagation with a Phantom V7.0 high speed camera at a rate of 1,000 frames per second and assuming that the front propagation speed is equal to the flame speed. This was a reasonable assumption given the small magnitude of the convective velocities $v$ used to establish the mixture stratification.

This burner was an extrapolation of our previous work with gaseous fuels. It has the advantage that it can be easily loaded with particles and that it assures reliable ignition and flame propagation, especially if the flames are methane assisted. However, in the coal case, it was not able to provide a wide range of fuel stratification because of the weak flow of the air stream and the small diffusivity of the coal particles. It is also evident that this design only allows for flame propagation into gradually leaner mixtures. For this reason, a counterflow burner was also established.

**b. Counterflow burner:** The overall experimental set-up is presented schematically in Figure 3. Fuel stratification was achieved by establishing a convective-diffusive balance in the fresh mixture in the counterflow configuration shown in Figure 4, which was a modification of the apparatus used in the previous experimental set-up based on Stefan flow. The reason we redesigned the chamber was to have better controllability of each boundary condition at both the top and the bottom. Two mixtures of different equivalence ratio were metered through the top and the bottom of the chamber with counterflow speeds of the order of 0.1-0.7 cm/s, so that the mixture was practically stagnant relatively to the flames that propagated in it after ignition. The cross-section of the chamber was 2x2 cm$^2$ and its length was 25 cm. Under the assumption of one-dimensional, isobaric and steady state conditions, the convective diffusive-balance in the chamber is described by the equation:

$$\rho v \frac{dY_f}{dx} = \rho D \frac{dY_f^2}{dx^2}$$  \hspace{1cm} (3)

where $Y_f$ is the fuel mixture fraction, $D$ the mass diffusivity, and $v$ the flow velocity, which in a counterflow configuration is on the form $v=-Kx$. It is reminded that the imposed strain here is very small, on the order of 0.01 s$^{-1}$. As a result of this, the general solution of (1), which is of the form:

$$Y_f = A \text{erf} \left( \frac{x}{(D/K)^{1/2}} \right) + B$$  \hspace{1cm} (4)

A, B, constants depending on boundary conditions describes thick mixing layers that develop over several cm and in which $Y_f$ appears almost linear. This can be also seen from (3), which shows that for a given diffusivity, as the counterflow velocity $v$ decreases, the distribution of $Y_f$ approaches linearity.
Fuel concentration in the cold mixture was measured using line-Raman imaging. The second harmonic of a Nd-YAG laser (532 nm) firing at 10 Hz rate with a pulse energy of 137 mJ was used as an excitation source. An HSPF-36193 holographic notch filter by Kaiser Optical System Inc. offering a nominal rejection of six orders of magnitude at 532 nm with a full width half maximum of 350 cm$^{-1}$ was used for rejection at the incident wavelength. A 3 mm thick OG550 long-pass orange glass filter was used for additional rejection. Scattered light was collected with a 50mm f/2.8 Nikon lens and dispersed with an Action Research 30 cm imaging spectrograph. The spectrograph output was coupled on the chip of an Andor DH-712 intensified CCD. The apparatus was appropriately synchronized with a DG535 digital delay/pulse generator of Stanford Research Inc. The Raman signal was proportional to methane number density in the isothermal cold mixture and was calibrated to a methane concentration by measuring signals of known composition. Fuel mass fraction and equivalence ratios were calculated from methane concentration and the realization that the total number density corresponded to atmospheric pressure and room temperature. It was assumed that methane fuel diffuses together with coal, an assumption that needs further verification.

Once a steady equivalence ratio distribution was established, the flame was ignited with a spark as shown in Figure 4 and propagated only downwards because the upward propagating flame was quenched by a steel wire screen. A manually operated valve on the top of the chamber was opened right before ignition in order to secure that the flames propagated isobarically. Flame speeds were measured by monitoring the propagation with a Phantom V7.0 high speed camera at a rate of 1000 frames per second with the assumption that the front propagation speeds were equal to the flame speeds, which was a reasonable assumption for the almost stagnant mixtures under consideration.

In addition to the flame speed measurements in the two burners, experimental equipment was used for velocity and particle size measurements.
c. **Particle Image Velocimetry speed measurement:** The experimental setup for velocity measurements in the burner included a Phantom v. 7.0 high speed camera coupled to a cooper vapor laser as well as the necessary optics shown in Figure 5 below. The coal particles were used as PIV markers. The setup uses prisms instead of a fiber optic cable to avoid degradation of laser ray quality. The ray is initially diverged and then converged to obtain a better focus before reaching plano concave lens. The plano-concave lens is used converge laser ray into a thin sheet.
A vital component of the experimental technique is optimal camera exposure since saturated images are not processed correctly by the PIV software. The recordings were processed with the Sleuth® PIV software developed in the University of Illinois at Urbana-Champaign.

d. Fraunhofer diffraction (Malvern) based measurement of particle size. In order to acquire droplet size measurements averaged along a line of sight, a Malvern Spraytec RTS 5000 spray analyzer was used to measure droplet sizes. A Class IIIb He Ne 5 mW Max CW diode laser was used to illuminate the droplets and the scattered light was collected and analyzed using Fraunhofer diffraction theory. A personal computer was used for instrument control, data acquisition, and processing. A maximum sampling frequency of 2500 Hz allowed a minimum time delay of 400 µs between samples.

RESULTS AND DISCUSSION

A fundamental result of high practical relevance that was established was that flames can propagate into mixtures that are theoretically beyond the flammability limits if they are back-supported by appropriate mixture stratification. Also the results are presented of efforts to perform PIV and Malvern measurements in coal-laden flows.

a. Flame propagation into gradually leaner mixtures Figure 6 provides flame speed measurements and equivalence ratio distributions for a series of propagation scenarios in several propagation scenarios. Caution is urged in that in each panel, two kinds of flame speeds are presented. The actually measured flame speeds in the stratified medium (cross symbols) are compared to the flame speed measured when the chamber was filled with a uniform mixture of equivalence ratio equal to the local equivalence ratio (circle symbols).
These latter speeds were found to be very close to the laminar adiabatic flame speeds reported in [10]. The only notable difference for the adiabatic case was that we were not able to ignite below $\phi < 0.58$ which was slightly higher than the lean flammability limit of $\phi \approx 0.5$ reported for adiabatic flames [11].

It can be seen that, when the mixture is far from the flammability limits ($0.7 < \phi < 1$, Figs. 6-c), the propagation can be envisioned in a “quasi-uniform” fashion with the

![Figure 6. Equivalence ratio and flame speed measurements in lean, compositionally stratified methane-air mixtures. Four pieces of information are presented in each panel: Distribution of $\phi$ (solid line), “quasi-homogeneous”, laminar flame speed corresponding to the local value of $\phi$ ($s_L$) (o), measured flame speed in the stratified mixture ($s'_L$) (x) and ratio of “quasi-homogeneous” over measured speed ($s_L / s'_L$).](image)

flame speed being practically equal to the adiabatic flame speed corresponding to the local equivalence ratio. The situation differs when the flame propagates through locations where the equivalence ratio in the unburnt mixture is closer to the flammability limit.
(0.5<\phi<0.7, Figs. 6-e). There, significant differences are observed between the measured flame speed in the stratified medium and the adiabatic flame speed for the local equivalence ratio. Notably, the results of Figs. 6e-f show a significant extension of the lean flammability limit for propagation in a stratified medium. Back-supported by heat released during combustion at equivalence ratios closer to stoichiometric, the flame can penetrate all the way to locations of $\phi \approx 0.35$, whereas in a homogeneous mixture, no flame can be ignited for $\phi < 0.58$. This difference manifests itself in a particularly striking way in the case of Figure 6f, where a flame is ignited right at the flammability limit in the stratified medium and can propagate in mixture compositions that are clearly subflammable. It is noted that non-quasi homogeneity becomes more apparent through higher flame speeds and extension of the lean flammability limit when flames experience larger equivalence gradients and leaner mixtures. The result is of high practical relevance because it shows that the notion of the flammability limit is to be treated with extreme caution when it comes to safety considerations. Back-supported by vigorously burning combustion, the flame can penetrate into clearly sub-flammable compositions in a compositionally stratified medium.

b. Propagation into near-stoichiometric and rich mixtures. The chemistry of flame propagation into near-stoichiometric and rich mixtures is significantly different than the one corresponding to lean mixtures, because the excess of oxidizer can be treated pretty much as chemically inert, which is clearly not the case for excessive fuel. A first issue that needs to be highlighted is the difference of the flames under consideration with the paradigm of the flat, adiabatic laminar flame. To this extent, we established mixtures of constant equivalence ratio in our apparatus by feeding mixtures of the same composition from both ends and measured the flame speed as a function of equivalence ratio. In Figure 7 the measured flame speeds are presented as a function of $\phi$ and compare with the adiabatic flame speeds calculated using CHEMKIN 4.1.1 for the case of methane fuel. It can be seen that the flames propagated with speeds higher than the adiabatic flame speed. This is attributed to the curvature of the flame front that could not be eliminated completely in the tubular apparatus of Figures. 2 and 4.

The front propagation speed in the centerline of the chamber being measured here, and flame curvature together with instabilities often introduces error in the estimation of this quantity.
Figure 7. Flame speeds in uniform mixtures. The solid line represents flame speed as a function of $\phi$ from CHEMKIN 4.1.1 calculations. The data points indicate flame speeds measured in homogeneous mixtures in our apparatus.

Keeping this consideration in mind, we compare two flame speeds in Figure 8. One is the actually measured speed of flames propagating in the stratified mixtures of cases (i)-(iv). A second quantity is the “quasi-homogeneous” speed, i.e. the flame speed measured in a homogeneous mixture with equivalence ratio equal to the local value of $\phi$ (as reported in Figure 7). In most cases, the flame speed during propagation in the stratified, gradually richer mixture is measured to be higher than the “quasi homogeneous” flame speed corresponding to the local equivalence ratio in the unburnt mixture. Supported by heat released during combustion closer-to-stoichiometric composition, the flames propagate with a speed significantly larger than the one corresponding to a homogeneous mixture. The related differences are much more pronounced than the ones reported in Figure 6 for lean mixtures. Indeed in case (iii) the ratio between the two speeds is on the order of two, whereas in the lean case differences on the order of maximum 50% were observed only in the vicinity of the lean flammability limit. In the rich case, significantly larger departures from quasi-homogeneity can be observed even for mixtures relatively close to stoichiometric composition, as opposed to the lean case, where the propagation was “quasi-homogeneous” for near stoichiometric mixtures. It should also be noted that, unlike the lean case the difference between the two speeds is non-monotonic with distance from the stoichiometric point. Indeed, it can be seen from Figure 6 that in lean mixtures the farther the flame propagated into the leaner mixture the larger the departure from quasi-homogeneity was. However, in the cases of rich mixtures (i) and (ii) the difference between the actually measured speed and the “quasi-homogeneous” speed initially increased, then decreased, and actually in mixture (i) we were able to observe “quasi-homogeneous” speeds that were higher than the actually measured flame speeds, something that was never observed in lean mixtures.
Evidently, from one point on, the heat “back-support” to the flame is not sufficient in order to compensate for the smaller energetic content of the richer mixture upstream of the flame.

The precise reasons for the differences between rich and lean stratified combustion will have to be investigated by considering radical concentration and temperature profiles,
which can be an interesting continuation of the work accomplished here. However, it is safe to attribute these differences to the fundamental asymmetry between the chemistry of lean and rich combustion. The lean case is a relatively simple one with the oxidizer remaining as a reactant that simply did not take part in the reaction. However the chemistry of the rich case is more complicated since the fuel does not survive the reaction and the combustion produces increasing amounts of CO and H₂ in increasingly richer mixtures.

Similarly to the lean case, an extension of the flammability limit is observed during stratified combustion. “Back-supported” by heat released during combustion that is close-to-stoichiometric, the flame is able to propagate into “super”-flammable mixtures, for which “quasi-homogeneous” flame speeds can of course not be measured and are therefore absent from Figure 8d. From Figure 8, it can be seen that this phenomenon becomes more prominent as we go from case (i) to case (iv), i.e. as the equivalence ratio gradient becomes steeper. Indeed, in case (iv) the flame was in the “super”-flammable region for the entirety of the optically accessible section of the chamber and propagated all the way to $\phi = 1.7$. The possibility of flame propagation in super-flammable mixtures may be of interest in the context of production of H₂ and CO. An equilibrium calculation with CHEMKIN 4.1.1 showed that for $\phi \approx 1.7$ mole fractions of H₂ and CO are expected to be as high as 12% and 10% respectively. Theoretical implications of these findings are presented in detail in [12].

c. Establishment of PIV measurements. The possibility to measure velocity field was established in coal-laden flows using Particle Image Velocimetry. Typical raw data are shown in Figure 9a and processed velocity fields in Figure 9b. The pulverized coal particles can be effective PIV seeds and, as shown in Figure 9b, speeds on the order of a few m/s were measured. This completed this feasibility study and no particular velocity fields were studied. An interesting issue emerged that can guide future investigations. It relates to the possibility of measuring coal particle and gaseous velocities using PIV in a coal laden flow. The gaseous flow can be measured by inserting into the flow fine alumina particles that will track the flow much better than the relatively large coal particles. Techniques will have to be established in order to distinguish between the signals used for the gas-phase and the condensed-phase velocities.

d. Particle size measurements. The measurements of coal particle size with the Malvern Instrument have so far been inconclusive. Particle-laden jets were investigated outside
the burners of Figures 2 and 4 in order to simplify the configuration and facilitate optical access to the degree possible. The non-transparent coal particles generated optically thick jets that did not yield measurable signals. In order to cure this, we have recently acquired (at no cost to ICCI) a more powerful laser that could be used for further investigations.

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this exploratory study, the following conclusions and recommendations can be supported:

- Optical and Laser-based diagnostics have the potential of revealing technically relevant characteristics of coal-laden flows. As an example, two well-characterized burners were devised, in which it was established that flames can advance into locations where the mixture is theoretically non-flammable, if the mixture composition is appropriately stratified.

- Pulverized coal particles are good tracers for PIV measurements of velocity fields. Once this has been established, the technique can be used in larger-scale burners than the experimental ones used in this exploratory study.

- The optical thickness (i.e. the non-transparency) of coal particles can hinder the application of various techniques. Such a challenge was encountered with Malvern-based particle-size measurements.

- Despite the challenges, laser diagnostics were shown to have useful applicability in coal-laden applications. It is recommended that the PI gets in contact with colleagues that have significant experience in coal in Illinois (e.g. ISGS, SIU) so that this activity is channeled in a way that will affect coal engineering most effectively. Guidance from the ICCI in this context will be very instrumental.

Figure 9b. Velocity field measured with PIV.
REFERENCES


DISCLAIMER STATEMENT

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