Spray Characterization Capabilities

March 2009

Since 1990, Energy Research Consultants (ERC) has studied and characterized a wide array of sprays for various applications in over 3,000 square feet of state of the art research facilities located in Laguna Hills, California. The following briefly describes the current capabilities in terms of facilities and diagnostics. ERC is continually evolving both facility and diagnostic capabilities and encourages discussion regarding applications for which the current capabilities appear to fall short.

Facilities

ERC has six test stands, three of which are primarily utilized for study of gas and liquid fired combustion systems and/or components. Three of the test stands are operated in an upfired manner and have exhausting capable of handling 6 lbs/sec of flow generated by devices fired with 1 MW of fuel input. All facilities offer 3 axes of traversing with digital readouts for relative position. The fluid delivery systems are interchangeable between the three stands.

Air. ERC has four independent air generation sources producing the following flows:

- 0.05 lbs/s (40 SCFM) at pressures up to 150 psig
- 0.15 lbs/s (120 SCFM) at pressures up to 125 psig
- 1.00 lbs/s at pressures up to 1.2 psig
- 2.00 lbs/s at pressures up to 3 psig.
- 0.80 lbs/sec at pressures up to 10 psig
- 37.5 lbs/sec at pressures up to 0.2 psig
- 1.0 lbs/sec vitiated air at 1340 F at 200 m/s

In addition, 50 kW of non-vitiated preheating is available. Monitoring of air pressure, flow, temperature, and humidity is available via transducers and associated data acquisition interfaces.

Liquid. ERC has experience running the following distillate and non-distillate liquids:

- Gasoline
- Diesel
- Calibration Fluid (MIL-C-7024D-Type II)
- Fischer-Tropsch derived
- Heptane
- Jet-A
- Acetone
- Viscor
- Bio Diesel
- Water
- Water/Glycerin

Five pumps are available:

- 1 gpm distillate fuel @ 300 psig
- 3 gpm water @3000 psig
- 10 gpm water @ 300 psig
- 100 gpm water @ 150 psig
- 1.4 gpm distillate fuel @ 600 psig

In addition, low pressure, low flow rate operation can be accomplished using an enclosed pressure container driving liquids with an inert gas pressure head up to 150 psig. In all cases, computer based monitoring of liquid flow rate, temperature and pressure is available via transducers and associated data acquisition interfaces. Multiple liquid circuits can be operated and monitored simultaneously (e.g., pilot and main stages).

Gaseous Fuel. ERC can flow up to 1.0 MW of natural gas. This can be used for vitiation. In addition, additional fuel handling to provide higher hydrocarbons such as ethane, propane and butane is available. Also, hydrogen and diluents such as carbon dioxide and nitrogen can be accommodated.

Diagnostics

ERC personnel have extensive experience with a wide range of non-intrusive optical diagnostics as applied to a variety of reacting and non-reacting sprays. Applications range from complex reacting gas turbine combustor environments to individual injector characterization under quiescent ambient conditions. In addition, a variety of conventional diagnostics are also available.

Optical Diagnostics

Laser Diffraction (LD). A Malvern 2600C laser diffraction particle sizer is available to provide line-of-sight measurement of particle size distributions and particle concentration. This well established method of characterizing sprays provides a relatively rapid and consistent measurement with little user controls. ERC has optical arrangements to facilitate measurement of fine particles (1.2 microns) to those approaching 2 mm in diameter. ERC personnel have extensive experience in optimizing optical setups, dealing with potential issues such as beam steering, sample clipping, correction for laser extinction, and presentation and interpretation of results obtained using LD.

Phase Doppler Interferometry(PDI). A two component phase Doppler interferometry system with frequency domain processing (both TSI FSA3500 and Aerometrics DSA 3200) is available which can be applied in a variety of ways. While primarily utilized to measure the joint distribution of particle size and two components of velocity at a point, it can also be utilized to measure flow field velocities in the absence of droplets or in the presence of droplets. Data reduction programs have been developed at ERC to provide tabulated results in a wide variety of formats. While more complex and time consuming to apply compared to LD, PDI provides considerably more information regarding the spray behavior and characteristics. In particular, it can provide the inlet conditions necessary for accurate computation fluid dynamics calculations. ERC personnel regularly apply PDI to both reacting and non-reacting sprays and have extensive experience in reducing and tabulating data for model validation and/or further interpretation, including time resolved details and frequency analysis. ERC has an exhaustive expertise of the limitations of the PDI technique and error analyses associated with these measurements.

Planar Elastic Light Scattering Imaging (PELSI). ERC maintains a variety of optics to produce sheets or beams of laser light from either cw (e.g., Ar^+) or pulsed (e.g., Nd:YAG) lasers. Such lighting, when scattered by the droplets, can be imaged onto an advanced CCD video camera (Canon L2 Hi-8). The camera can operate as both a video recorder or as a digital still camera with full user control over exposure (aperture and shutter speed). Close-up adapters are available to provide up to 30X magnification. In addition, ERC has the capability to extract frames from the video to conduct analysis (e.g., line profiles, comparison of images, etc.) as well as produce high quality video presentation of phenomena of interest. Various filters are utilized to isolate laser wavelengths and chemiluminescence from species of interest. The Nd:YAG laser can generate 4 ns pulses with energy levels sufficient to “freeze” the spray structure even with extreme magnification. This is useful in characterizing the highly complex breakup region.

Planar Liquid Laser Induced Fluorescence (PLLIF). A technique related to PELSI is planar liquid laser induced fluorescence (PLLIF). In this case, rather than obtaining qualitative images, fluorescence is utilized to provide quantitative characterization of the spatial distribution of the liquid material.

Optical Patternation. Extending the PLIFF technique, ERC has completed a Phase II SBIR program to develop a quantitative approach to the characterization of the spatial and temporal distribution of sprays (“optical patternation”). The technique corrects for both the attenuation of the incident light as it travels through the spray and the signal as it travels from the spray to the camera. A UV sensitive, intensified 16-bit CCD camera is available for quantitative optical patternation.

Infrared Extinction/Scattering (IRES). ERC has the capability to measure the time-averaged concentration of vapor present within unconfined hydrocarbon sprays using a two-wavelength extinction technique. While a line-of-sight technique, spatially resolved information can be obtained for axisymmetric fields by deconvolving a series of parallel scans. This technique has been utilized to obtain time-resolved information as well.

High Speed Visualization. High speed video up to 100,000 frames per sec with 1 microsecond exposure.

Particle Image Velocimetry (PIV). Measurements of particle velocity by tracking particle displacement with double pulsed laser and imaging.

Conventional Diagnostics

Emissions. For reacting sprays, ERC has the capability of measuring emissions including unburned hydrocarbons, oxygen, carbon monoxide, carbon dioxide, and oxides of nitrogen. In-situ samples are obtained using water-cooled extractive probes. ERC has implemented sophisticated data reduction tools for quality assurance, analysis, interpretation, and presentation of results. The spatial distribution of gaseous fuel can be determined through the use of microprobes and a flame ionization detector.

Temperature. A variety of thermocouples are utilized to obtain in-situ temperature measurements.

Calibration Devices. ERC has a wide variety of calibration devices, methods, and experience for quality control of all diagnostics and instrumentation.

CFD Modeling

ERC applies commercial CFD codes (Fluent or CFD-ACE) to model spray behavior.

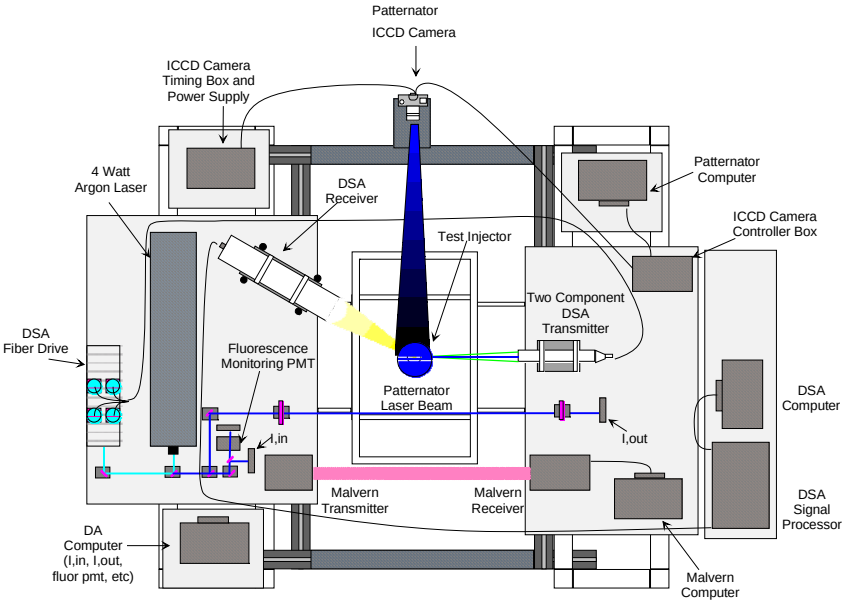
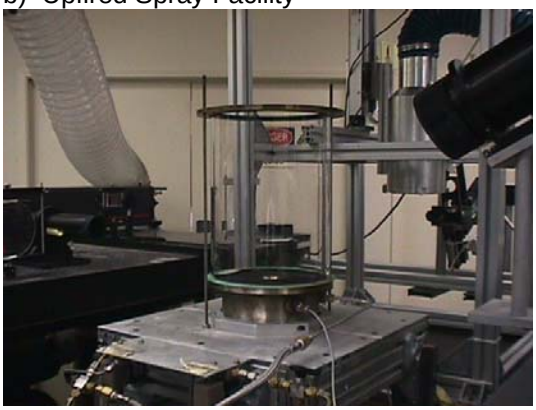


Figure 1. Schematic of Typical Spray Stand Setup and Some of the Available Diagnostics (Top View).

a) Upfired Multistage Combustor Evaluation

b) Upfired Spray Facility



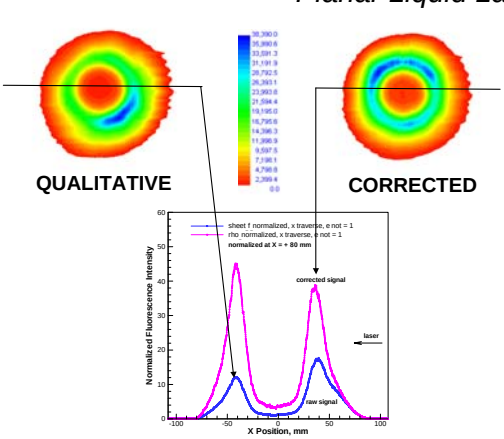
c) Emissions Analyzers, Test Stand

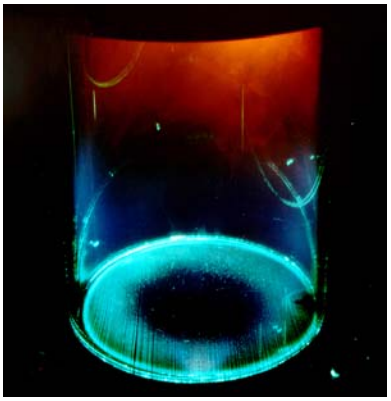
d) High Capacity Spray Facility

e) Vitiator

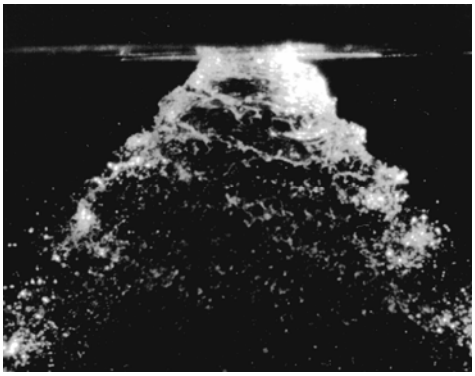
Figure 2. Available Test Stands.

Planar Liquid Laser Induced Fluorescence





Visualization



Phase Doppler Interferometry

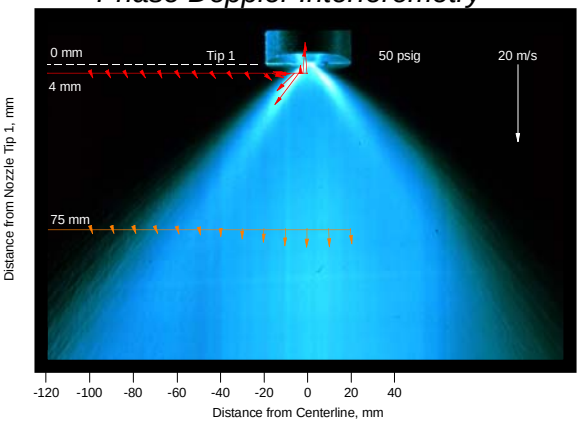


Figure 3. Example Spray Measurements.

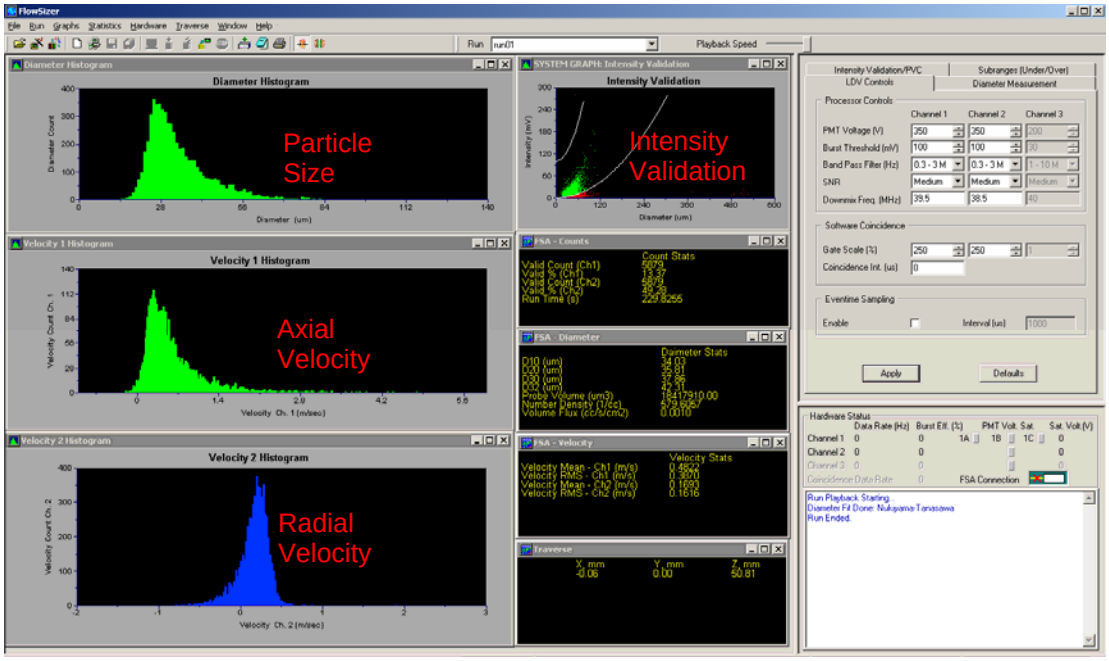


Figure 4. Sample PDI Number Distributions.

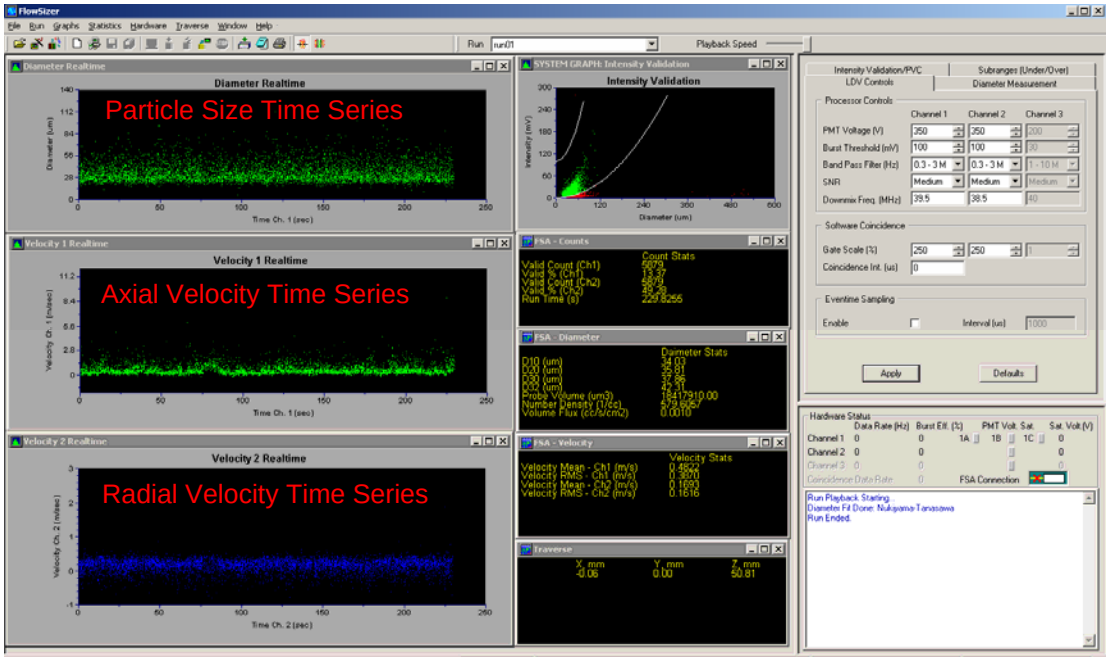


Figure 5. Sample PDI Time Series.

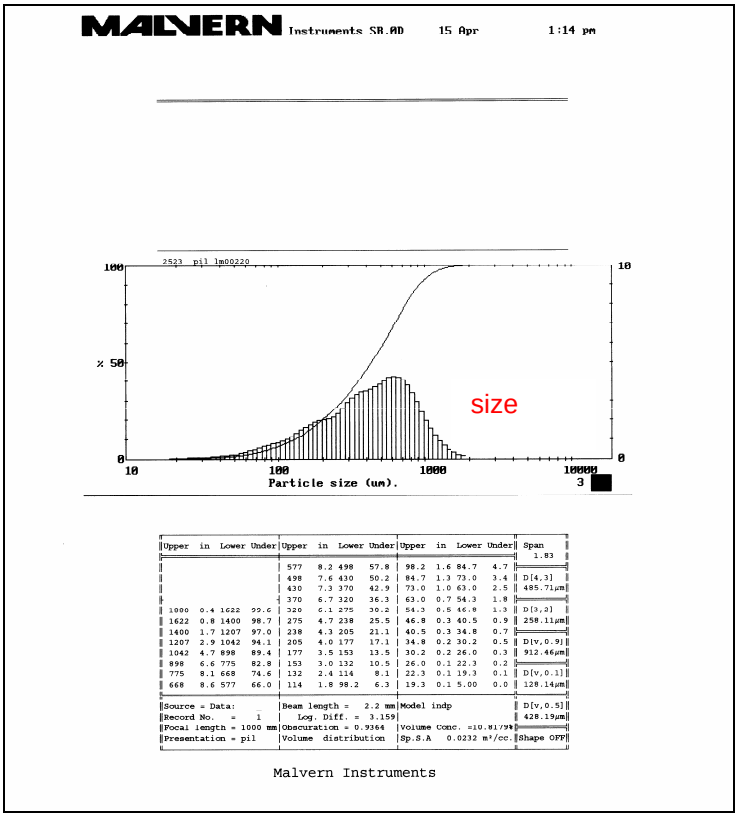


Figure 6. Sample LD Volume Distribution.

Table 1. ERC Facilities Specifications.

Item	Detailed Description
Rigs	6 rigs (TSI and II) (SSI, II, III, IV)
Air Supply	Air Supply 1 800 scfm (1 lbs/sec) at 1.2 psig Air Supply 2 1600 scfm (2 lbs/sec) at 3 psig Air Supply 3 640scfm (0.8 lbs/sec) at 10 psig Air Supply 4 40 scfm (0.05 lbs/sec) at 150 psig Air Supply 5 30,000 scfm (37.5 lbs/sec) at 0.2 psig
Air Preheating	Non-vitiated electric air preheating up to 50 kW
Liquid Fuel Supply	Fuel Supply 1 1.0 gpm fuel at 300 psig Fuel Supply 2 1.4 gpm fuel at 600 psig Fuel Supply 3 10 gpm water at 300 psig Fuel Supply 4 3 gpm water at 3000 psig Fuel Supply 5 100 gpm water at 150 psig Fuel Supply 6 pressure container handling up to 150 psig * flows and pressure depend on exact fluids used ** Fluids can be operated in single use or recycling mode
Gaseous Fuel Supply	Natural gas at 60 scfm (3.6 Million BTU/hr, 1MW) at 20 psig Gaseous fuel cylinders as needed
Exhausting	Exhausting at 5000 cfm at 4 inches water
Liquid Fuel types	Water Calibration fluid (stoddard solvent, fuel oil) Jet A Diesel fuel Gasoline Heptane Water / Glycerin Acetone Viscor

Table 1. ERC Facilities Specifications (concluded).

Item	Detailed Descriptoin
Diagnostics	Qualitative optical patternation Quantitative optical patternernation Phase Doppler Interferometry (including fiber optic transmitters) Laser Doppler Anemometry (including fiber optic transmitters) Particle Image Velocimetry (PIV) Laser Diffraction Flow visualization High Speed Video Laser Sheet visualization with Planar Elastic Light Scattering Imaging Laser Induced Fluorescence (LIF) Planar Laser Induced Fluorescence (PLIF) OH Planar Laser Induced Fluorescence (OH PLIF) Mixing using intrusive probe and hydrocarbon analyzer FID IRES IR Absorption Chemiluminescence Spectrophotometer with temperature control Spectrometer Emissions (HC cold and hot, O2, CO, CO2, NO, NOX) w/ sampling probes Liquid spray flux sampling probes CFD modeling Photography Video editing and preparation
Traversing and Hardware Interfacing	3 translational degrees, 1 rotational degree Digital readout of position with RS232 output SS1 21 inch basket SS2 60 inch basket Practical hardware interfacing design and fabrication Up-fired and down-fired configurations
Lasers	Coherent Innova 70-4, 4 watt Argon Ion Laser Coherent Innova 90-5, 5 watt Argon Ion Laser (quantity 2) Continuum Surelite I-10, 10 Hz repetition Rate, 50 mJ at 266 nm, 450 mJ at 1064 nm, 4-6 ns pulsewidth at 266 nm and 5-7 ns pulsewidth at 1064 nm Helium Neon Laser (0.6328 microns) Helium Neon Laser (3.39 microns)
Instrumentation	Traditional (thermocouples, pressure gauges and rotometers for example) and state of the art data acquisition systems (LabView) High Speed Pressure Transducers
Miscellaneous	High volume seeding for LDA

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