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[illegible]a, Y[illegible]Y. Chen, and R.W. Dibble
[illegible]sity[illegible] at Berkeley, Berkeley, California

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Ensemble Diffraction Measurements of Spray Combustion in a Novel Vitiated Coflow Turbulent Jet Flame Burner

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October 2000

Acknowledgments

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Ensemble Diffraction Measurements of Spray Combustion in a Novel Vitiated Coflow Turbulent Jet Flame Burner[1]

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ABSTRACT

An experimental investigation is presented of a novel vitiated coflow spray flame burner. The vitiated coflow emulates the recirculation region of most combustors, such as gas turbines or furnaces; additionally, since the vitiated gases are coflowing, the burner allows exploration of the chemistry of recirculation without the corresponding fluid mechanics of recirculation. As such, this burner allows for chemical kinetic model development without obscurations caused by fluid mechanics.

The burner consists of a central fuel jet (droplet or gaseous) surrounded by the oxygen rich combustion products of a lean premixed flame that is stabilized on a perforated, brass plate. The design presented allows for the reacting coflow to span a large range of temperatures and oxygen concentrations. Several experiments measuring the relationships between mixture stoichiometry and flame temperature are used to map out the operating ranges of the coflow burner. These include temperatures as low 300C to stoichiometric and oxygen concentrations from 18% to zero. This is achieved by stabilizing hydrogen-air premixed flames on a perforated plate. Furthermore, all of the CO_2 generated is from the jet combustion. Thus, a probe sample of NO_X and CO_2 yields uniquely an emission index, as is commonly done in gas turbine engine exhaust research.

The ability to adjust the oxygen content of the coflow allows us to steadily increase the coflow temperature surrounding the jet. At some temperature, the jet ignites far downstream from the injector tube. Further increases in the coflow temperature results in autoignition occurring closer to the nozzle. Examples are given of methane jetting into a coflow that is lean, stoichiometric, and even rich. Furthermore, an air jet with a rich coflow produced a normal looking flame that is actually 'inverted' (air on the inside, surrounded by fuel).

In the special case of spray injection, we demonstrate the efficacy of this novel burner with a methanol spray in a vitiated coflow. As a proof of concept, an ensemble light diffraction (ELD) optical instrument was used to conduct preliminary measurements of droplet size distribution and liquid volume fraction.

[1] Part of an ongoing project supported by NASA Glenn Research Center NAG3-2103.
[2] Presently with Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI), Tokyo, Japan

INTRODUCTION

A key ingredient of advanced combustor design is the back mixing of hot combustion products with incoming fuel and air (that is mixed to some level). This important feature is absent in the widely studied simple jet flames issuing into a coflow of air. In order to have mixing with products and try to maintain simplicity, past research used a bluff body to stabilize flames. In such bluff body flames, the physics of recirculation is strongly coupled to the chemistry, and independent variation of either the mixing or the chemistry is impossible. Furthermore, strong mixing mode or weak chemistry is often not allowed in the bluff body configuration due to flame blow out. Two experimental configurations overcome the limitations of the bluff body stabilized flame:

1. Coaxial jet into a coflow of hot combustion products (vitiated coflow).
2. Turbulent opposed jet flow where one jet could be reactants and the other jet products of combustion.

Both configurations allow intense turbulent mixing while maintaining a stable flame, thus providing the opportunity to examine turbulent mixing and combustion under the flow conditions typical of advanced combustors. Moreover, both configurations are especially amenable to computational explorations as well as optical diagnostics.

Several candidate configurations for the coaxial jet flame burner have been extensively investigated experimentally to identify their merits and shortcomings. A summary of the design selection process is included in Appendix B. Based on experimental findings, the novel jet flame burner has been developed. The oxygen rich combustion products of a lean premixed flame, stabilized on a perforated brass plate, surround the central fuel jet. A schematic of the vitiated coflow combustor is presented below in Figure 1, while some images of gaseous and liquid jets can be seen in Figure 2. No igniter is needed since the fuel emerging from the central fuel jet autoignites as it mixes with the hot coflow stream.

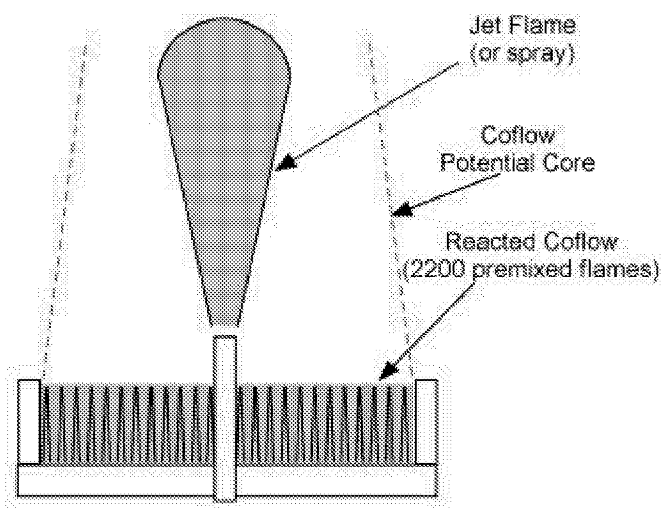
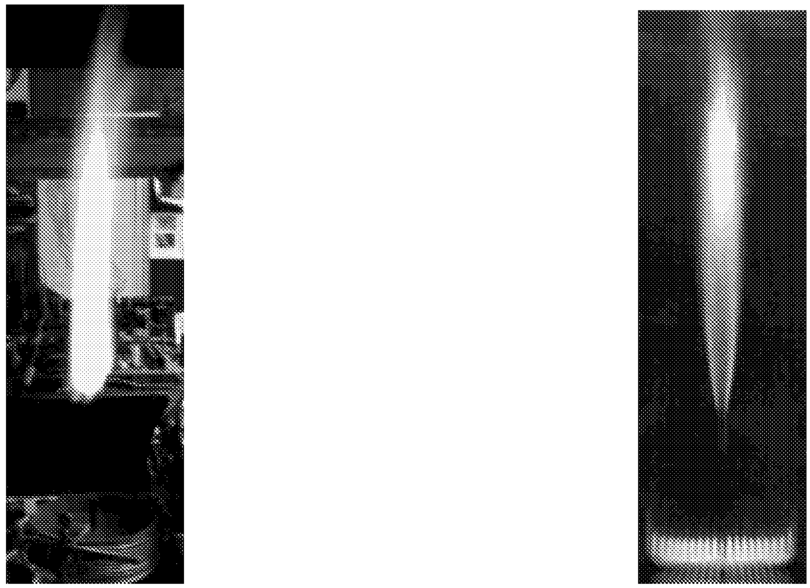


Figure 1.
Vitiated Coflow Flame



(a) Methanol spray in hydrogen-air coflow **(b)** Methane gas jet in methane-air coflow

Figure 2.
Photographic images of spray and gas jet in a vitiated coflow.

There are several types of flames that can be studied in this combustor. One interesting test that has been observed consisted of a rich methane coflow with an air jet. Figure 3 below shows an image from this experiment. The reverse diffusion flame is actually 'inside out'.

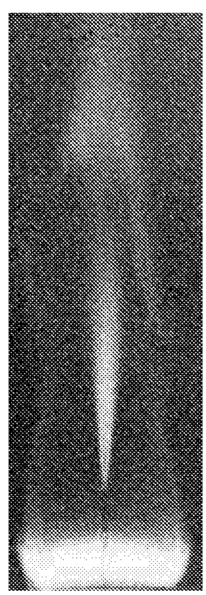


Figure 3.
An air jet in a rich coflow of methane and air.

The simple coaxial jet configuration allows for the investigation of salient features of advanced combustors, providing better fundamental understanding of interactions between turbulence and chemistry. Specifically, the simple geometry experimental condition will provide a critical screening/testing of current as well as emerging numerical models. Because the burner has open optical access, a wide range of investigations with this novel burner is expected.

Experiments on this burner have begun to produce data that are being incorporated into numerical models of combustion. The combined experimental and modeling effort will provide important information regarding:

1.) The impact of unmixedness on flame characteristics in terms of stability and pollution emissions.
2.) The structure of flames under highly turbulent flow regimes, where mixing and reactions are more intense than what would be encountered in a gas turbine engine. This is a necessity for improved models that span a wide range of conditions.
3.) The potential benefits of improving the interactions between chemistry and turbulence by using better mixing models and reduced chemistry.

The objectives of these experimental and numerical research efforts are to transfer fundamental knowledge gained from the coaxial jet flame study to industry and to provide essential information leading to the development of mechanistic models for pollution emissions. These models contain information heretofore unavailable and as such will provide the best insight and guidance in design and construction of advance combustion in gas turbine engines, both in aircraft and stationary power generation applications.

EXPERIMENTAL SETUP

Perforated Plate Turbulent Premixed Burner

The burner consists of three main components, coflow mixture supply, flashback chamber, and flame holder assembly. A schematic of the burner assembly is shown below in Figure 4. A 1.5-hp blower supplies the coflow air. The coflow fuel is injected at the blower inlet to produce a well-mixed mixture. The mixture travels through a plastic, 4inch diameter hose before it expands into the flashback chamber and exits out through the perforated plate. The central jet also enters through the flashback chamber and exits through the center of the perforated plate.

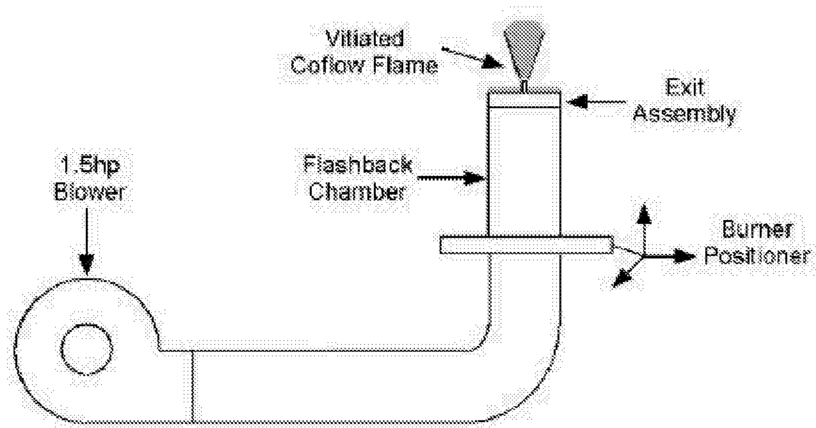


Figure 4.
Vitiated Coflow Combustor Schematic.

The flashback chamber is an 8 inch pipe size stainless steel compartment capable of withstanding an increase of pressure and temperature due to flashback. A schematic and picture of the flashback chamber and flame holder assembly are shown in Figure 5. In the midsection of this chamber, a 7.5 inch diameter by 2.5 inch thick uncoated ceramic monolith with 2x2 mm channels provides an excellent flashback arrestor and flow straightener.

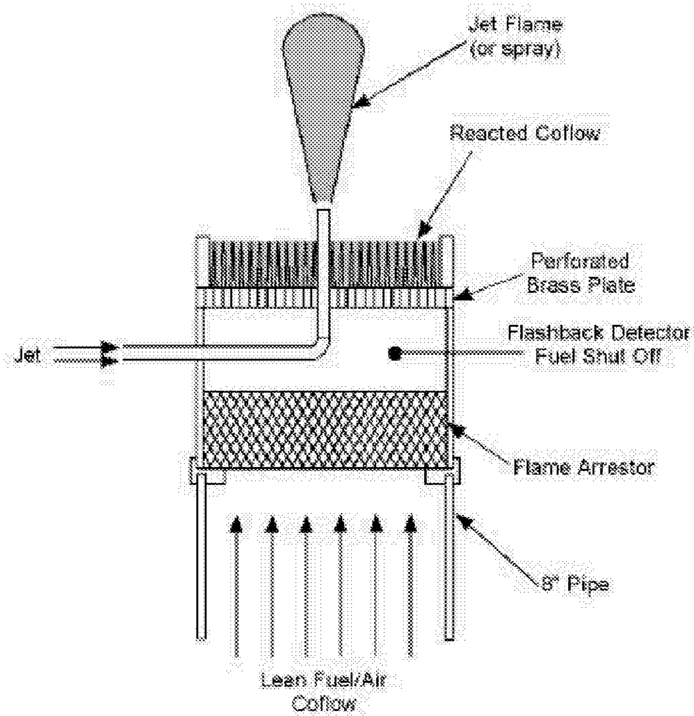
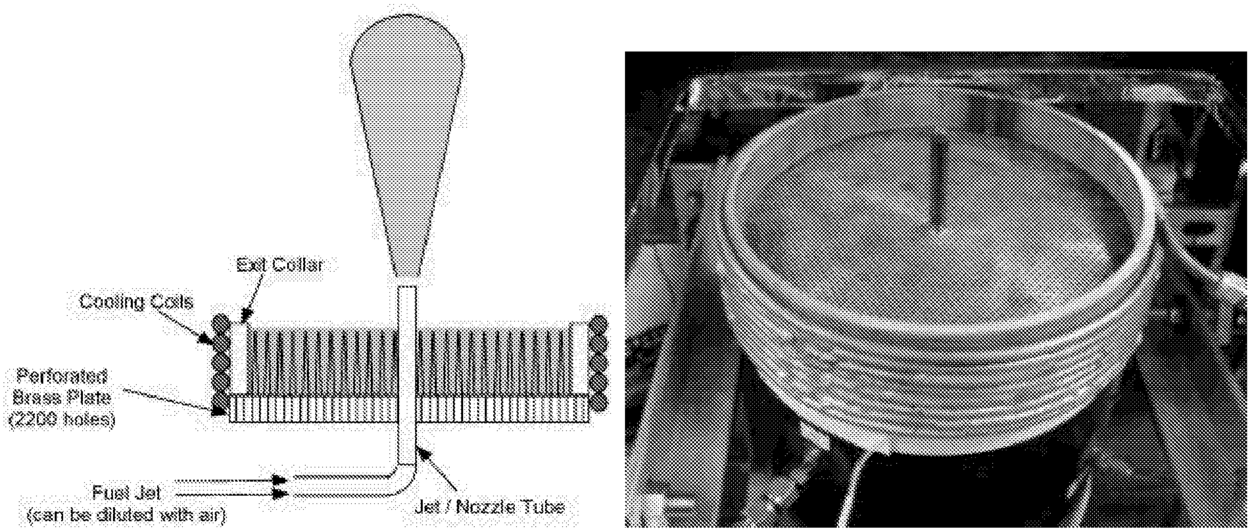


Figure 5.
Flashback Chamber

The perforated plate is an excellent flame holder. However, the fuel-air mixture poses a substantial threat of flashback. Flashback is the propagation of the flame upstream through the holes of the perforated plate possibly generating explosive conditions. Therefore a flashback sensor assembly was designed to automatically cut off the coflow fuel at any slight increase in pressure or temperature. Secondly, the flashback arrestor provides a cold barrier for the flame. This safety system proved to be quick and reliable by a series of tests where the premixed gases upstream of the perforated plate were intentionally ignited.

The flame holder assembly consists of the perforated plate, exit collar and center jet (Figure 6). The perforated plate has diameter and thickness dimensions of 8.75 and ½ inches respectively. A numerical machine (CNC) drilled the 2200 holes (1/16 inch diameter) necessary to achieve a blockage of 87%. A wide variety of hydrocarbon-premixed flames over a range of stoichiometries can be stabilized on the rapid heat dissipating brass. An exit collar provides a barrier that creates a complete, uniform, flat flame by preventing the entrainment of ambient air. A water coil, only to minimize the radiation from the metal, cools this collar.



(a) Schematic **(b)** Photo

Figure 6.
Flame holder Assembly

The flame of interest is held above the coflow flame tips such that the coflow can be assumed uniform at the jet exit. This flame can be a fuel jet or liquid spray that both could be diluted by air. We have recently demonstrated the entire flat flame burner with central fuel jet concept with fuel jets of methane into the hot coflow and with sprays of methanol into the hot coflow. Color pictures of these events are included in the presentation and at http:/euler.me.berkeley.edu/cal.

Burner Range of Capabilities

A comprehensive control and safety system was developed for the vitiated coflow burner. Coflow fuel flow rate is supplied by bottles and measured with sonic-flow orifice meters. A 1.5hp blower, controlled by a frequency control, supplies the coflow airflow rate. Besides controlling the flow rates, an oxygen sensor measures the oxygen content of the products and a type K thermocouple measures the flame temperature. A computer running the software LabVIEW by *National Instruments* reads all electronic sensor outputs.

A series of experiments were conducted to map out the operation range of this burner. The coflow was set at a mass flow rate of 40 g/s of air that has a cold bulk velocity of 1 m/s. The flame temperature and stoichiometry were measured for each case and the results are plotted in Figure 7 for the hydrogen-air mixture and in Figure 8 for the methane-air mixture. On both plots, the results are compared with those of an adiabatic reaction. As can be seen from the plots, there is a certain amount of heat loss that can be attributed to the heat transfer with the perforated plate and the water-cooled collar by the recirculation at these surfaces. Before getting to the blow off point, the hydrogen mixture had a stoichiometry of 0.17 and a temperature of 560 K compared to a stoichiometry of 0.53 and temperature of 1120 K for methane. The upper limit was constrained by the amount of heat produced by these flames that can generate on the order of several hundred kW of thermal power.

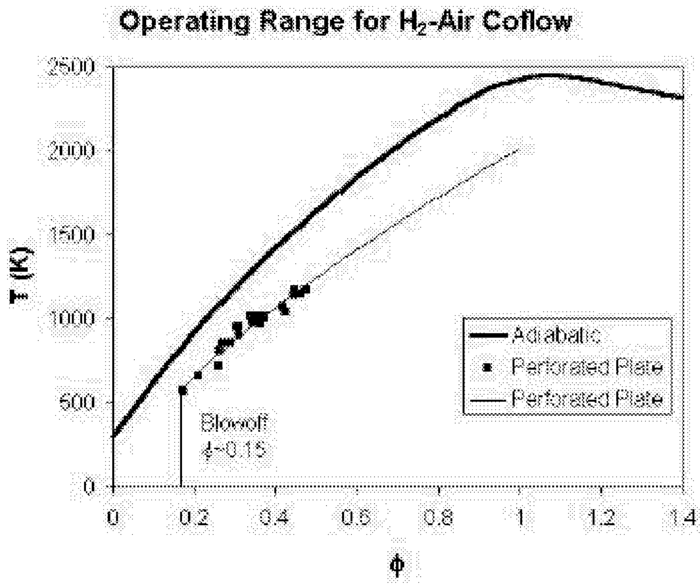


Figure 7.
Temperature vs. fuel to air ratio for hydrogen-air coflow.

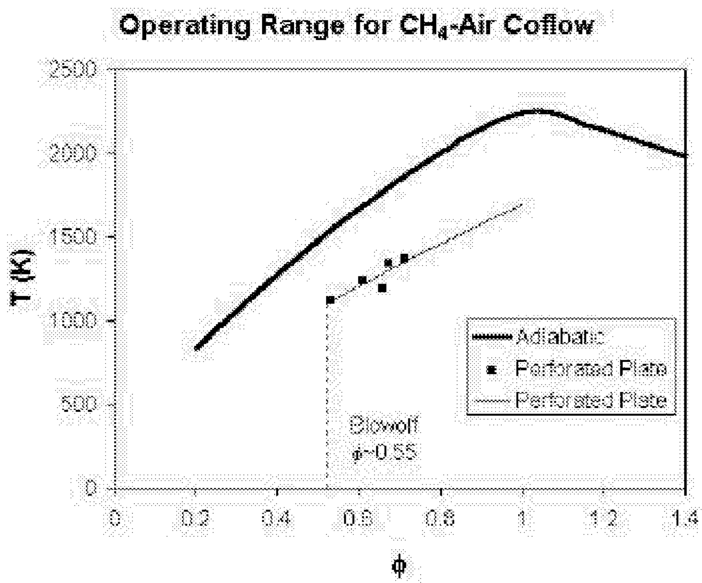


Figure 8.
Temperature vs. fuel to air ratio for methane-air coflow.

The preceding data shows that a wide range of hydrogen-air turbulent premixed flames can be stabilized on the perforated plate burner. Accordingly, this combustor has the capacity for the exploration of a large range of Damköhler numbers.

Ensemble Light Diffraction (ELD) Optical System

The *Malvern/INSITEC* EPCS (Ensemble Particle Concentration and Size) instrument system is designed to continuously measure and feed back particle size distribution information from mixtures of aerosols or powder. The EPCS uses the ensemble light diffraction (ELD) technique to measure the particle size distribution. This system implements the fraunhofer theory that gives the relationship between the angle at which the beam is scattered by a particle, and the size of that particle.

Figure 9 shows a schematic of the EPCS unit. The system consists of a laser diode, lens and two detectors. The laser is a 670nm, ~5mW laser diode. The scattering detector has log-scaled annular detectors at various radii and a small center hole through which the incident beam passes. The incident beam is focused at a sharp point at the center of the second detector, giving a measure of the transmission through the spray. A computer running the RTSIZER (Real Time particle SIZER) by *Malvern/INSITEC* executes the data reduction. An image of the system is included in the presentation, Appendix D.

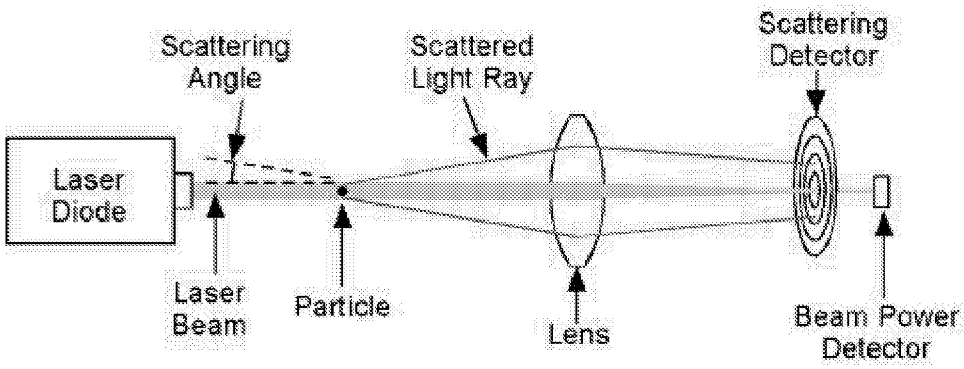


Figure 9.
Ensemble Light Diffraction Optical System.

Based on the geometry of the system, the scattering detector provides the capability to measure the light intensity for several scattering angles. The particle size distribution is then calculated:

$$S(q_i) = \sum_j C_{i,j} V(d_j) \qquad (1.)$$

Using the scattering signal $S(\theta_i)$ the system calculates a discretized particle size distribution $V(d_j)$ via a transform function $C_{i,j}$. The transform function is determined by particle and system optical properties.

The beam power detector measures the transmission through the spray. The Beer-Lambert Law relates this transmission to the volume concentration of the particles.

$$T = e^{-(1.5 C_V L Q / D_{32})} \qquad (2.)$$

The transmission T is measured while the Sauter mean diameter of the particle size distribution D_{32} is calculated via the distribution $V(d_j)$. The optical path length L is approximated via the vertical position and the manufacturer specified spray angle. The light scattering efficiency Q depends on the instrument geometry and is approximately 2 for most cases. The volume concentration C_v is desired and can be readily calculated with the known parameters and equation (2).

Spray Nozzle

For this study a nozzle provides the spray flame of methanol. The Delavan fuel Nozzle (#67700-5) has a 45° spray angle and a fuel number of 0.7. A drawing of this nozzle is included in Appendix C. The fuel number determines the mass flow rate given the backpressure on the nozzle.

$$FN = \left(\frac{\dot{m}(\mathrm{lb/hr})}{\sqrt{P(\mathrm{psi})}} \right) \quad (3.)$$

$$\dot{m}(\mathrm{kg/s}) = FN\sqrt{P(\mathrm{psi})}\left(1.26x10^{-4} \frac{\mathrm{kg/s}}{\mathrm{lb/hr}} \right) \quad (4.)$$

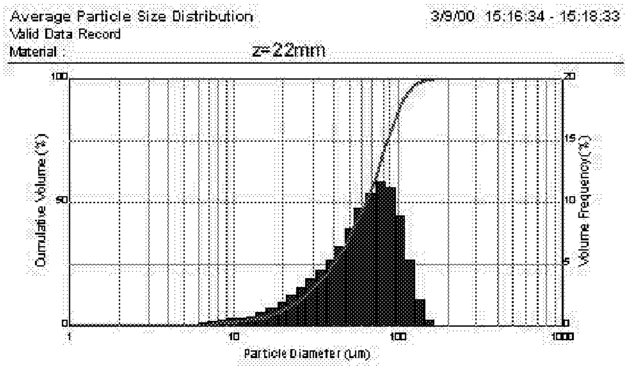
For this experiment, the nozzle pressure was set at 35 psi, giving a methanol mass flow rate of ~0.5 g/s. The nozzle exit is 63 mm above the perforated plate surface. The coflow had a flow rate of 40 g/s for air and 0.35 g/s for hydrogen (ϕ=0.3), the cold bulk flow had a velocity of 1 m/s. The resulting temperature was 955 K. The amount of thermal energy produced by the coflow is 50 kW, while the spray generates 10 kW.

RESULTS AND DISCUSSION

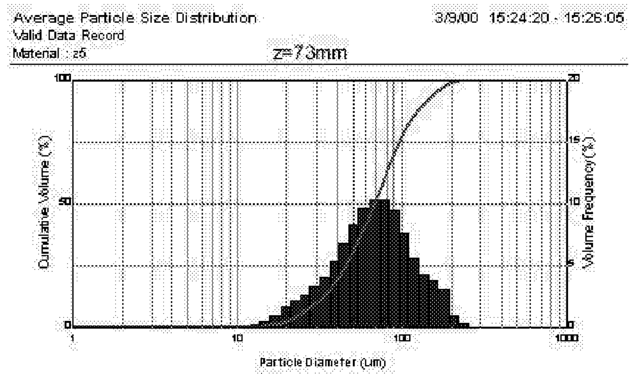
The flame measured is shown below in Figure 10. As can be seen, the orange plume is a source of high radiation, which had to be accounted for and is discussed later in this section. This orange light is due to the high temperature sodium impurities of the methanol spray.

Figure 10.
Images of the methanol spray flame.

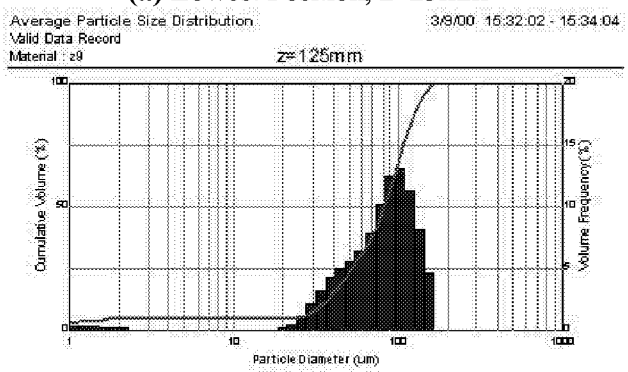
Presented below in Figures 11a-d are the droplet size distributions for three vertical positions, at the lowest position (22mm above the nozzle exit), at the spray mid-section (halfway up), and at the flame front. In total, nine vertical positions were investigated, the complete set of droplet size distributions are presented in Appendix A.



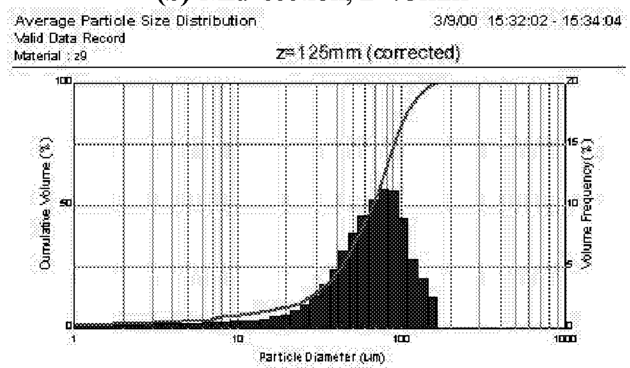
(a) Lowest Position, z=23mm



(b) Mid-section, z=73mm



(c) Flame Front, z=125mm



(d) Flame Front, z=125mm (corrected)

Figure 11.
Particle size distributions at three vertical positions.

Although it was a stable spray flame, the flame front did fluctuate in and out of the laser beam path at z = 125mm above the nozzle. Due to the radiation of the flame, the rings measured added intensity. Since the ring detector areas are log scaled (smaller areas closer to the center), the outer rings detect more and more of this radiation, thus giving false readings for the small end of the size distribution. This can be seen in Figure 11c where particle sizes between 1-3μm are reported to have significant populations. This data set was corrected by omitting the outer detector rings from the calculations; the corrected size distribution is shown in Figure 11d.

It seems apparent that the droplet sizes do not change considerably until the droplets actually reach the flame front. Along with the droplet size distribution, the cumulative volume percentage is also plotted in Figures 11a-d. An accepted measure of the average particle size is the 50% volume diameter $D_V(50)$, which is the diameter under which 50% of the cumulative volume exists. The half volume diameter for each vertical position was plotted on Figure 12 below. The only deviation from the relatively uniform droplet size occurs at the flame front, and for this calculation the data was not corrected for the flame radiation. There is no significant change in droplet size between the nozzle and the flame front.

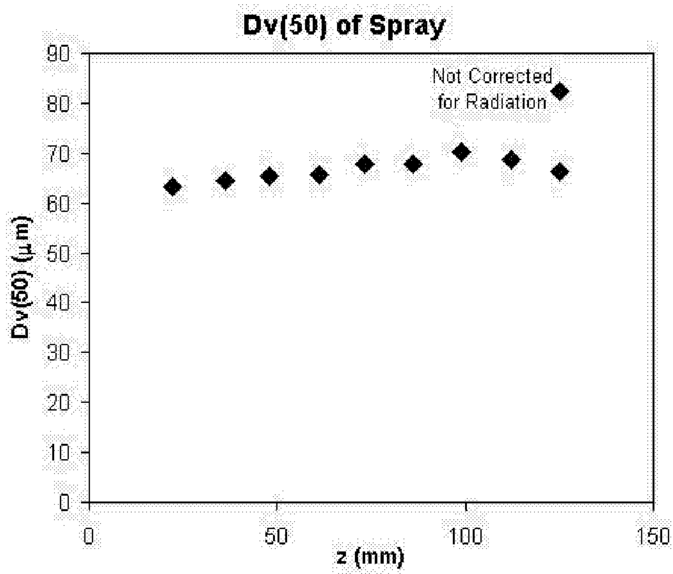


Figure 12.
Dv(50) of spray vs. vertical position.

Another measure of the spray is the volume concentration of droplets. The change in the volume concentration in the spray is shown below in Figure 13. For these calculations, the Delevan specified spray angle of 45° was incorporated to determine the path length L used in equation (2) to determine the volume concentration. As can be seen in the figure, this change in concentration is not significantly different from its change due strictly to droplet divergence. In other words, the area of the spray at any vertical position is proportional to z^2, subsequently the concentration is proportional $1/z^2$ which is approximately the same relationship shown in Figure 13.

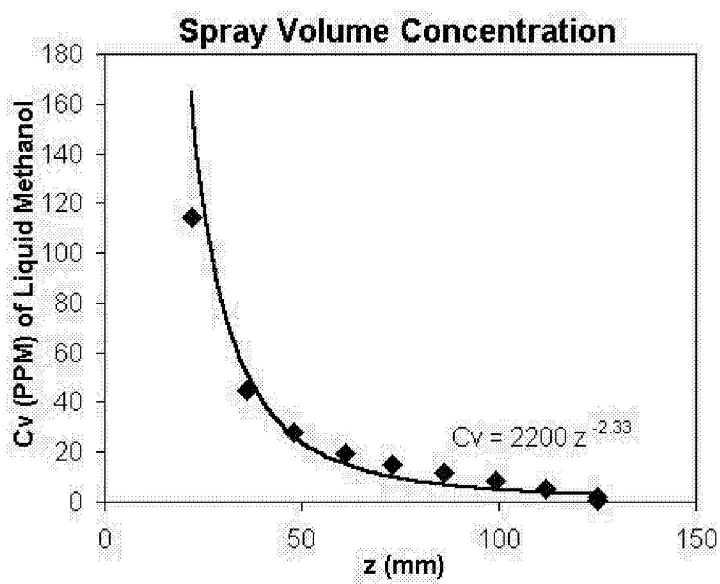


Figure 13.
Spray volume concentration vs. vertical position

The results given here is the first step in the investigation of a liquid spray in a vitiated coflow. Droplet sizes remain uniform in the spray region between the nozzle exit and the flame front and subsequently; the volume concentration diminishes with the spreading of the spray. With these results, one may want to assert that the time over which the droplets evaporate and burn is extremely short and that the hot coflow has little impact on the liquid spray up until that point. However, due to time constraints and the small number conducted tests, these and any conclusions would be premature.

Currently, the effort to study these liquid sprays in hot coflow continues. The vertical position of the flame front has been observed to be dependent on the coflow stoichiometry and temperature. Global emissions of the spray must also be measured. Therefore further investigations of methanol sprays are needed in addition to possible diesel, kerosene or water sprays.

Ongoing research efforts on the vitiated coflow gaseous jet flame are focused on the laser Raman scattering that will be performed at the Combustion Research Facility at Sandia National Laboratories. The overall objective is to provide a simple burner and a database of measurements for a number of liquid and gaseous fuel jets.

CONCLUSIONS

The vitiated coflow combustor presented here provides a flame where the recirculation chemistry inherent in many combustion systems is decoupled from the associated recirculation fluid mechanics. The exhaust products emanating from a perforated brass plate burner are the coflow oxidizer for the jet flame (liquid or gas) that emerges from the center of the perforated plate disk. With a hydrocarbon fuel jet emerging from the center of the hydrogen co-flow premixed flame, all of the CO_2 generated is from the jet combustion. Thus, a probe sample of NO_X and CO_2 yields uniquely an emission index, as is commonly done in gas turbine engine exhaust research.

Adjusting the coflow stoichiometry varies the coflow oxidizer temperature. A map of the operating ranges for the burner was developed; these include temperatures as low 300C and oxygen concentrations of 18%. Hence, this burner can be used to investigate a large number of flames.

Optical measurements of a methanol flame provide preliminary information of the behavior of sprays surrounded by hot oxygen, nitrogen and water. Even though the findings present some interesting behavior in the spray, no conclusion can be made until more experiments can be conducted to confirm the data.

REFERENCES

Blevins, R. *Applied Fluid Dynamics Handbook.* Krieger Publishing Company. 1992

Fristrom, R. M.. *Flame Structure and Processes*. Oxford University Press. 1995

Kean, A., Schlegel, A., and Dibble, R.W.. “Experimental and Numerical Instigation of NO_x Emissions from a Propane Fueled Hybrid Catalytic Combustor.” WSS/CI 98S57. 1998

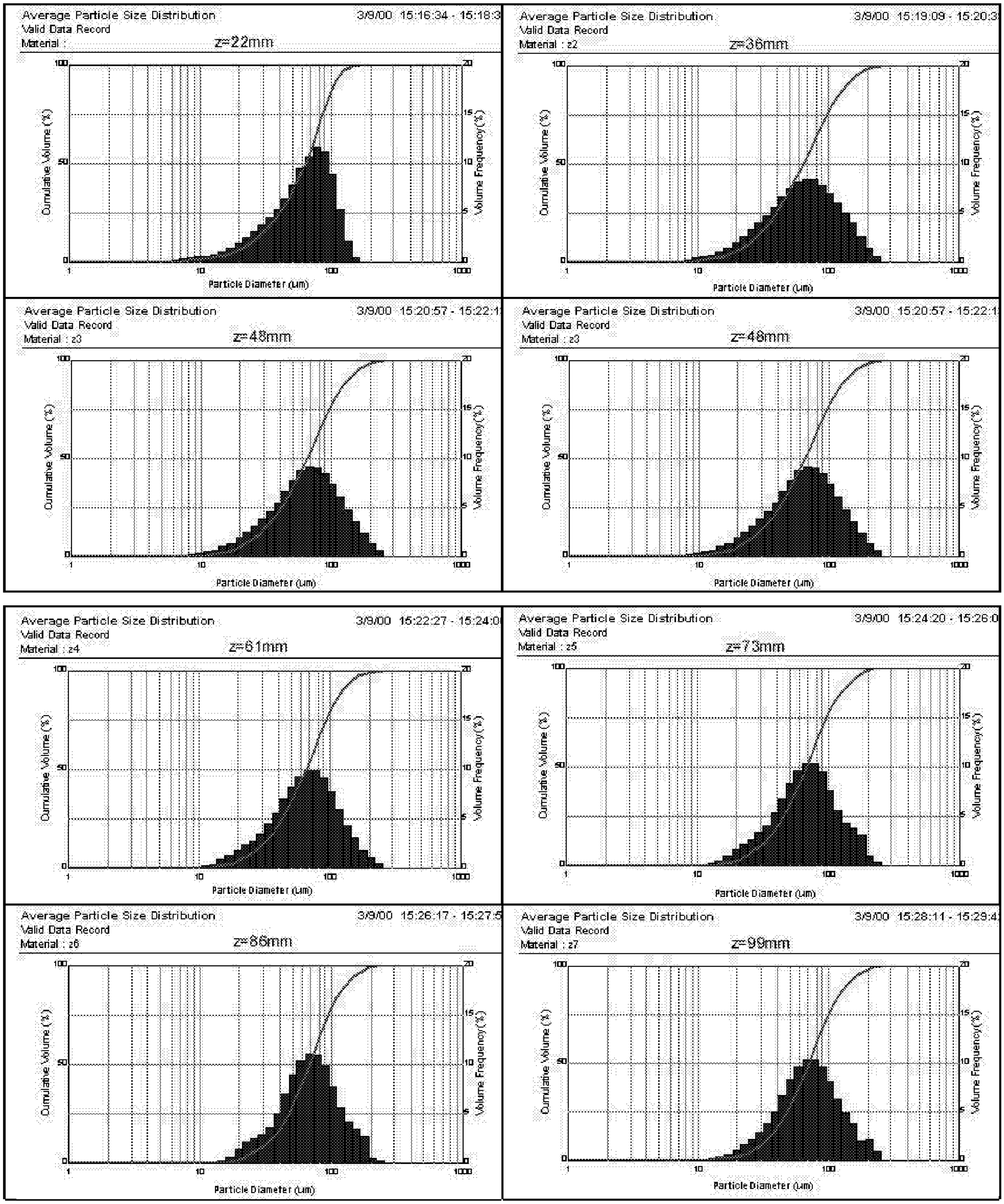
Warnatz, J., Maas, U., and Dibble, R.W.. *Combustion: Physical and Chemical Fundamentals, Modeling and Simulation, Experiments, Pollutant Formation.* Springer-Verlag. 1999

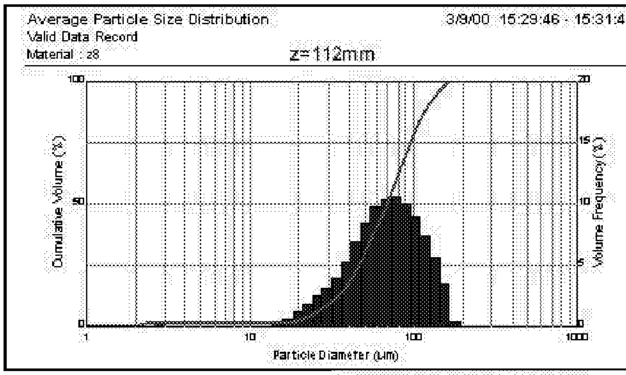
‘*Malvern/INSITEC* Technical Specifications: EPCS’, *Malvern/INSITEC.* 1998

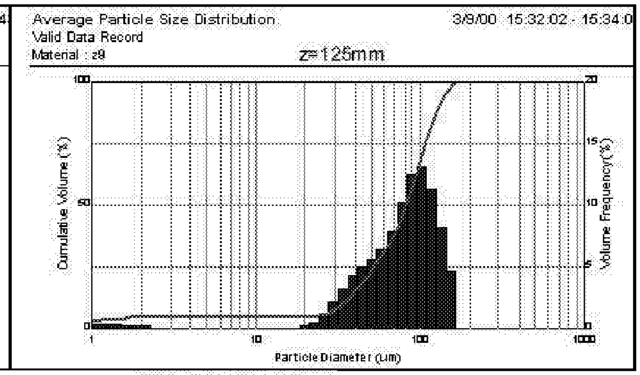
Appendix A.

Complete set of droplet size distributions for each vertical position

Z is the vertical distance from the nozzle exit.




Average Particle Size Distribution
3/9/00 15:29:46 - 15:31:4
Valid Data Record
Material : z8
z=112mm
Cumulative Volume (%)
Volume Frequency (%)
Particle Diameter (um)


Average Particle Size Distribution
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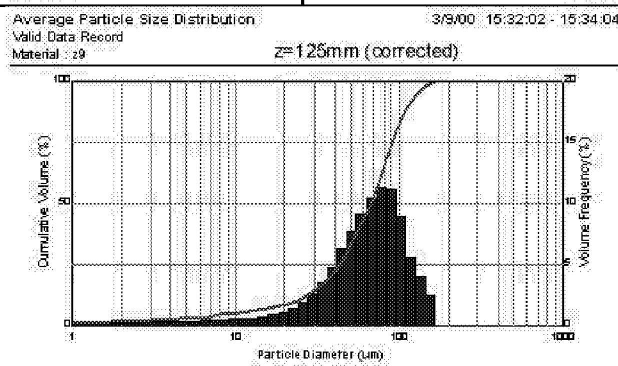
Valid Data Record
Material : z9
z=125mm
Cumulative Volume (%)
Volume Frequency (%)
Particle Diameter (um)


Average Particle Size Distribution
3/9/00 15:32:02 - 15:34:04
Valid Data Record
Material : z9
z=125mm (corrected)
Cumulative Volume (%)
Volume Frequency (%)
Particle Diameter (um)

Appendix B.
Combustor Design Selection

The design objective was to create a combustor where a flame is completely surrounded by a coflow of hot products (vitiated) from an upstream flame or catalyst rather than cold, ambient air. In order for the testing volume to be significant, a large area coflow is needed.

In brief, the experimental program is to study a jet with a coflow. However, the coflow must be designed to have hot coflowing products (vitiated) as the oxidizer instead of simply air. In this way, a parabolic jet flow, with excellent optical access, can emulate the recirculation zone of a gas turbine combustor. In time, we expect that the central jet can be rich, lean, swirling, and contain droplets. Thus, we see this burner as a workbench for a wide variety of flows. Accordingly, it was most important that we select a coflow burner that would be usable for all of the above applications. Below, we describe the several burner configurations that we considered.

1. **Catalytic Burner:** A 2 inch diameter prototype combustor was built to test the design effectiveness [Kean et al 1998]. The catalysts used consisted of platinum supported on a ceramic straight-channel monolith (200 cells per square inch), similar to those used in automotive catalytic converters. The total length of catalysts was 10 cm. The fuels used in this burner were CH_4+H_2 and C_3H_8+H_2. The equivalence ratio tested was as low as 0.3 and the flow velocity was on the order of 1 m/s. This design proved too difficult to maintain a stable, centered jet flame.

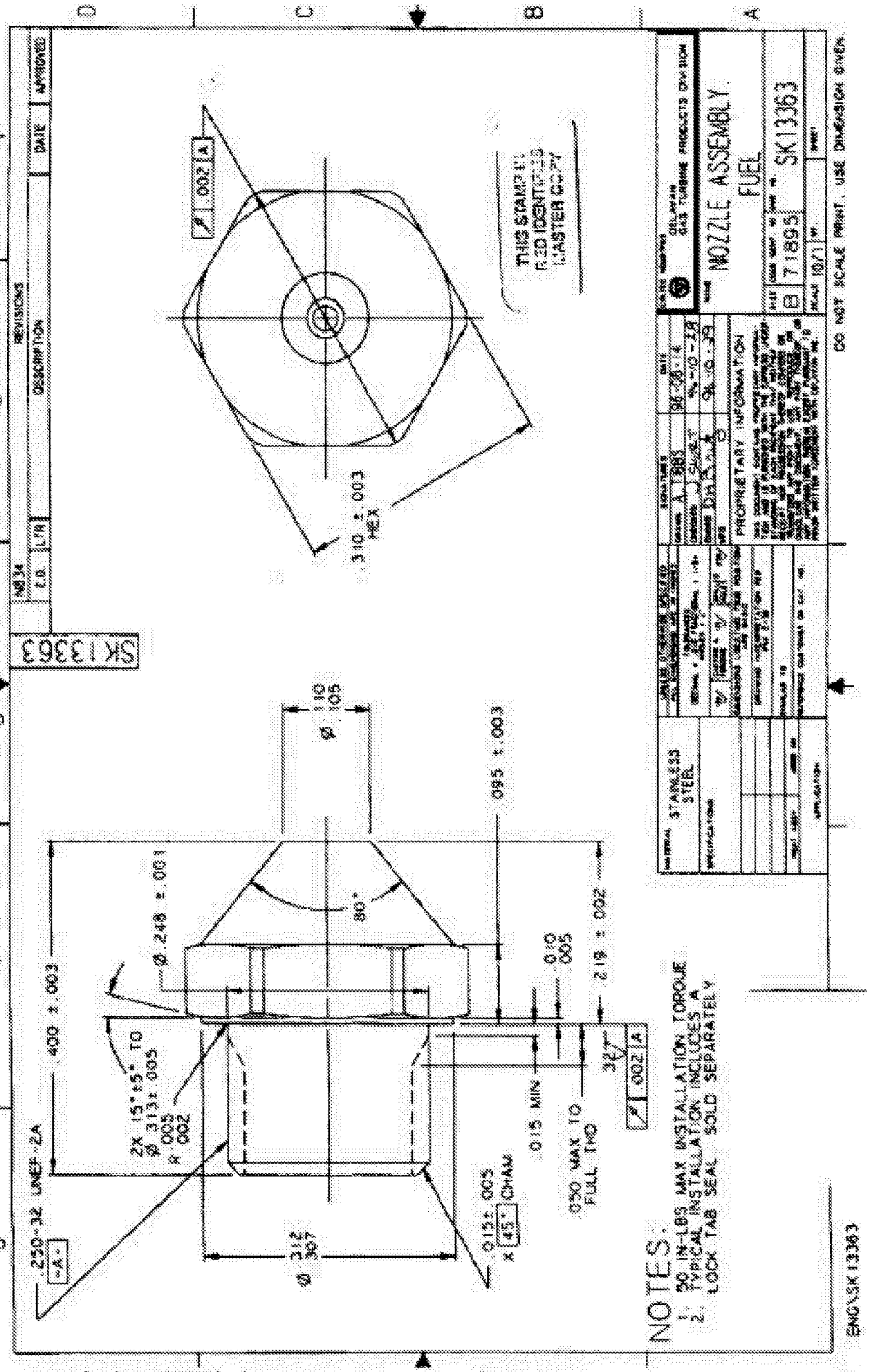
2. **Coarse Porous Disk Burner**: Following the same idea as grid turbulence burner (see #4), a 2 inch coarse porous ceramic disk replaced the wire screen. There was no observable improvement over the grid turbulent burner. Furthermore, there is no simple way to add LDV or PIV particles to this flow.

3. **Tube Bundle Burner:** A 2 inch burner was constructed using 300 3/32 inch tubes. These 3/32 inch tubes were arranged in a square pattern with gaps between adjacent tubes. Fuel and air injection into the burner was performed by two methods. In the first case, fuel flowed through the tubes, while air flowed through the interstices surrounding the tubes. This setup did not produce a sufficiently flat flame. In a second test, this injection pattern was reversed: air flowed through the tubes, while fuel flowed around the tubes. A flat flame was achieved with this setup. The lowest overall equivalence ratio achieved was 0.3 and the average speed at the burner exit was about 2 m/s. This burner is a spin-off of the multiple diffusion flame burner described in the text by Fristrom (1995) where he cites the research of Berl and Wilson (1961). More recently, this burner is often called a 'Hencken burner' after commercial supplier (Hencken, Dublin CA.). The virtues of this burner are mitigated by the expense when made in the 20 cm diameter burner used here.

4. **Grid/Perforated Plate Turbulent Premixed Burner:** A premixed grid turbulence burner is a cylindrical duct topped by a stainless steel screen at the exit plane. A low equivalence ratio of 0.6 and velocity of 2 m/s was achieved with a fuel mixture of H2+CH4. Preliminary explorations of a perforated-plate burner with 85% blockage showed great promise. One drawback is the possibility of flashback into the mixing chamber.

After reviewing all of the designs, the perforated plate burner proved to be the most successful flame holder. Premixed methane in air, and hydrogen in air flames are flat, stable, and lean. The system also has a rather large range of operating conditions.

Appendix C.
Delavan Fuel Nozzle



Appendix D.
Presentation of this paper at the 2000 Spring Meeting of the Western States Section of The Combustion Institute
Colorado School of Mines, Golden, Colorado

Ensemble Diffraction Measurements of Spray Combustion in a Novel Vitiated Coflow Turbulent Jet Flame Burner

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Process Metrix

F. Acosta and D. Holve
Process Metrix, LLC, San Ramon, CA

Part of an ongoing project funded by

WSS/CI 00S-47

Preliminary Optical Spray Measurements on New Burner

- New, robust vitiated coflow burner
- Proof of concept, operating limits
- Ensemble light diffraction (ELD) technique measures the particle size distribution

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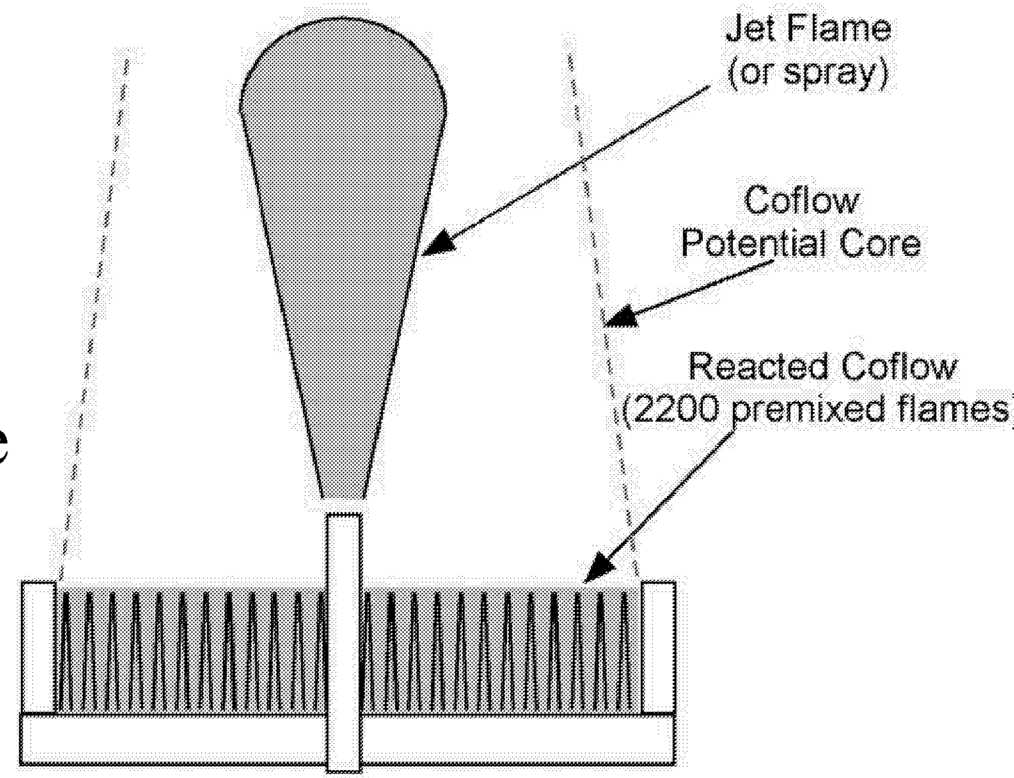
Target: Recirculation Chemistry

- No recirculation fluid mechanics
- Lean premixed H_2-air coflow
- Jet/Spray: Only source of CO & CO_2
- Large range of Damköhler #'s



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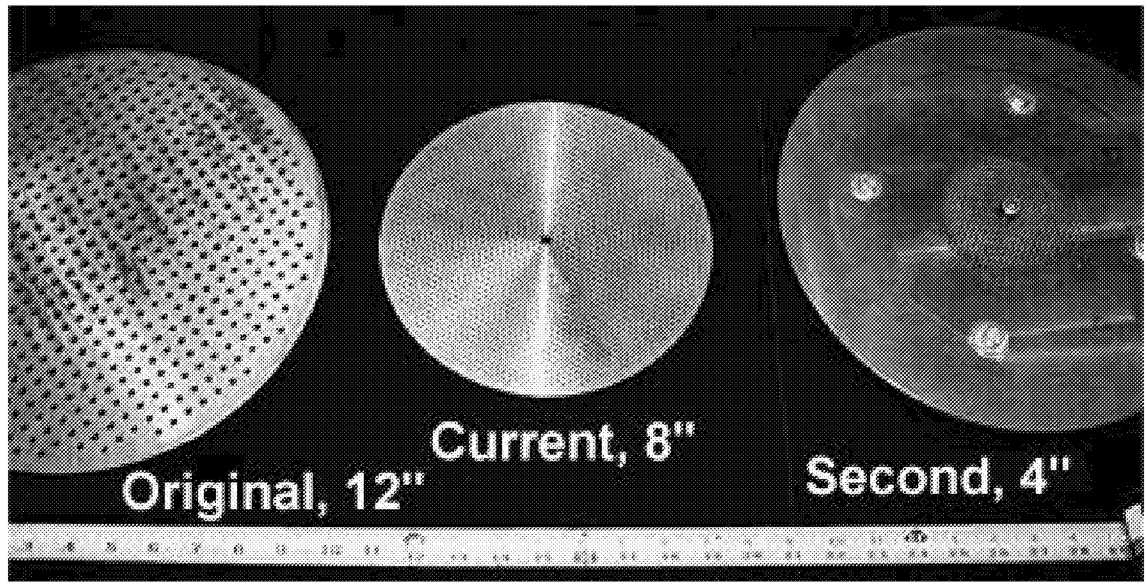
8” Diameter Perforated Area Proved to be Just Right.

Design Factors

- Large coflow potential core
- Thermal power generation
- Air flow rate requirements



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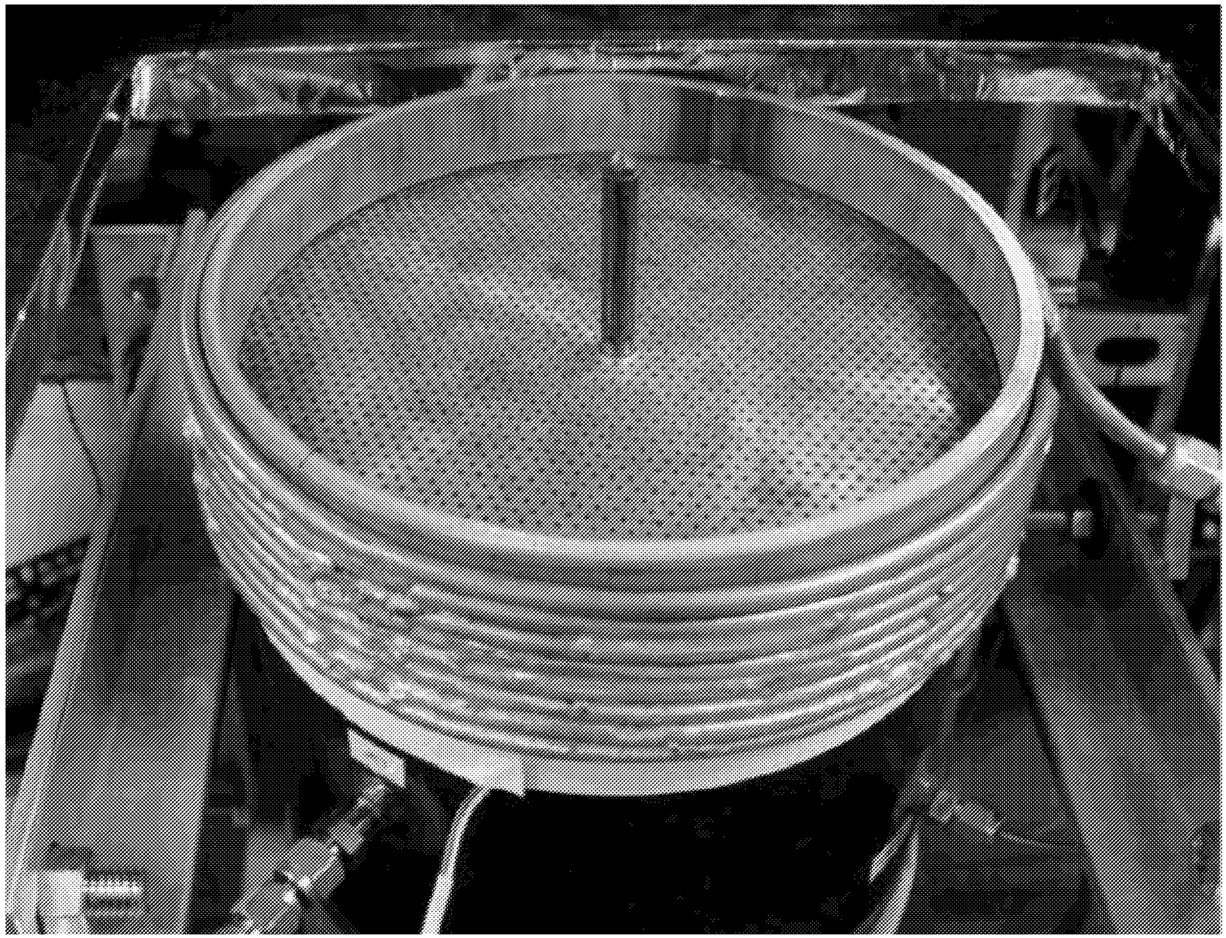
Vitiated Coflow Combustor



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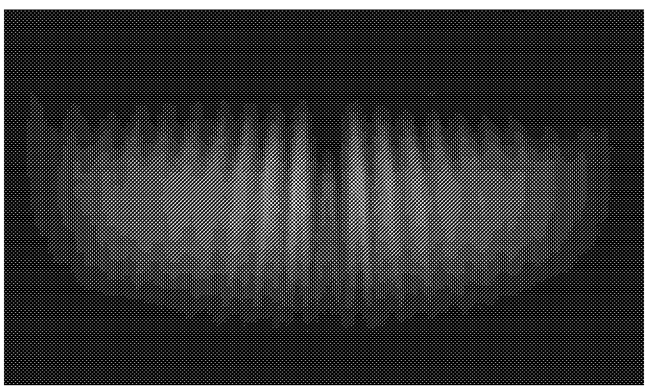
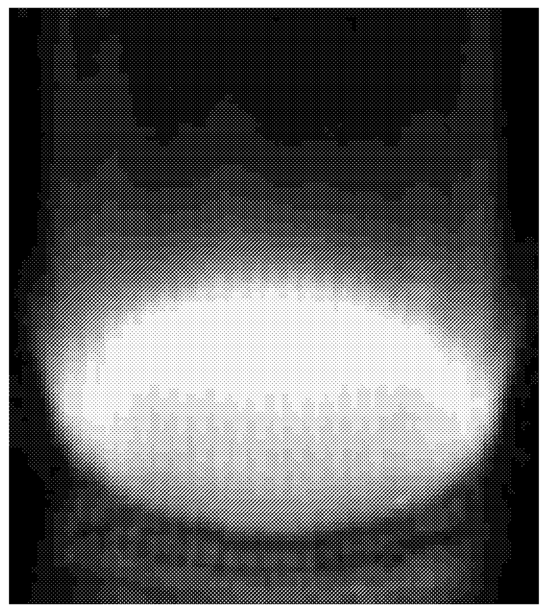
Vitiated Coflow

- Control coflow temperature by the adjustment of stoichiometry

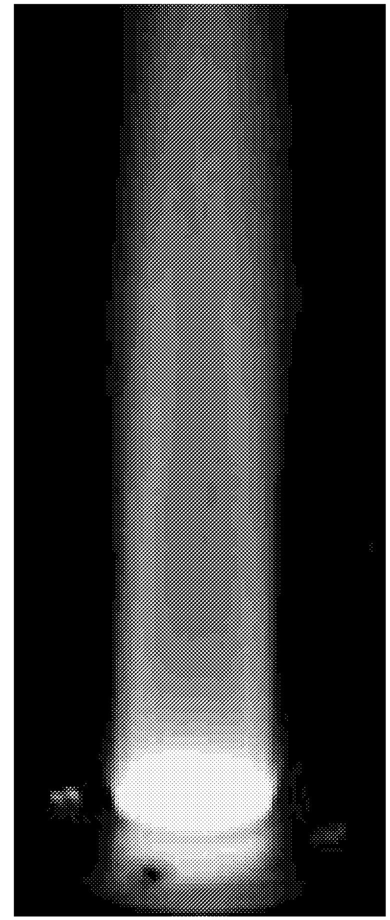
Lean



Rich



$\phi \sim 1$



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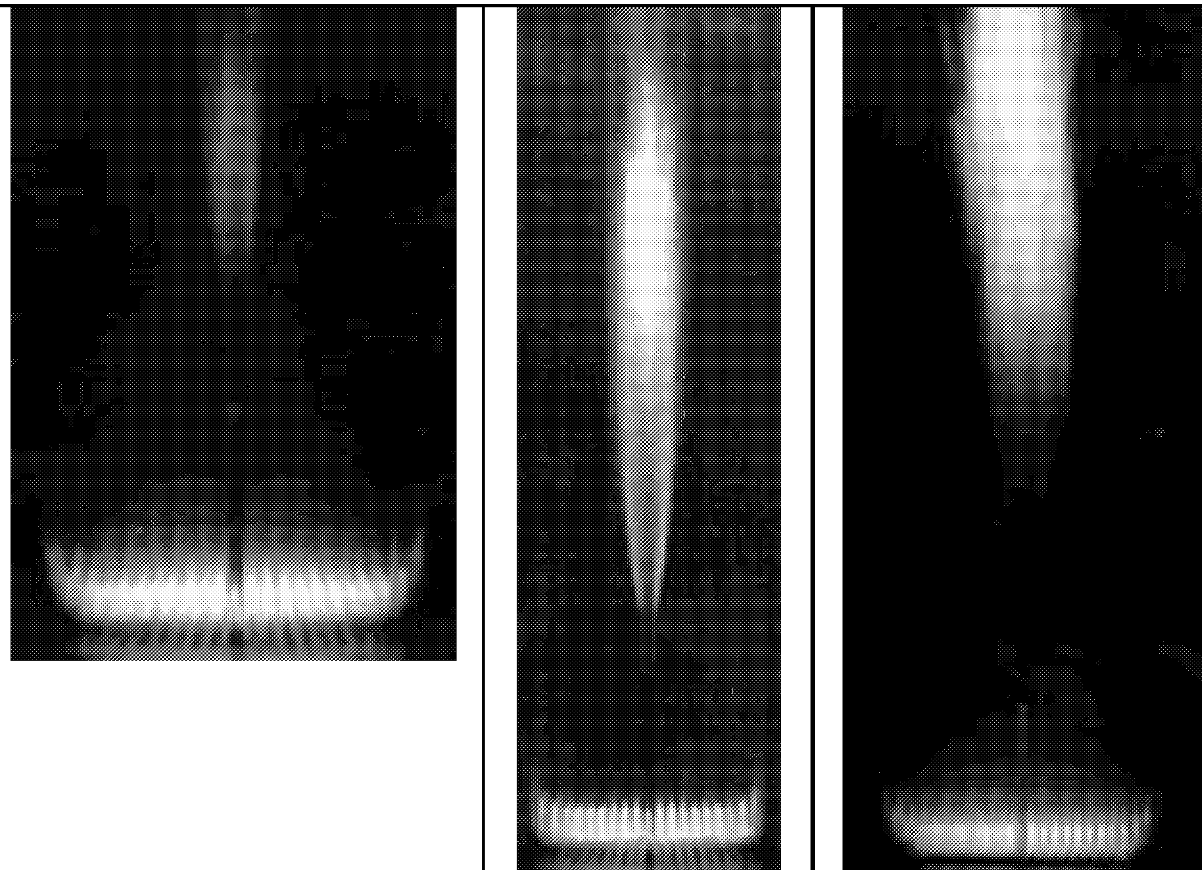
Jets in Lean Coflow



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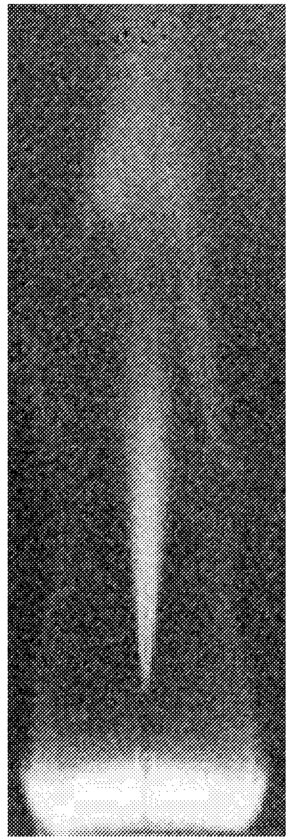
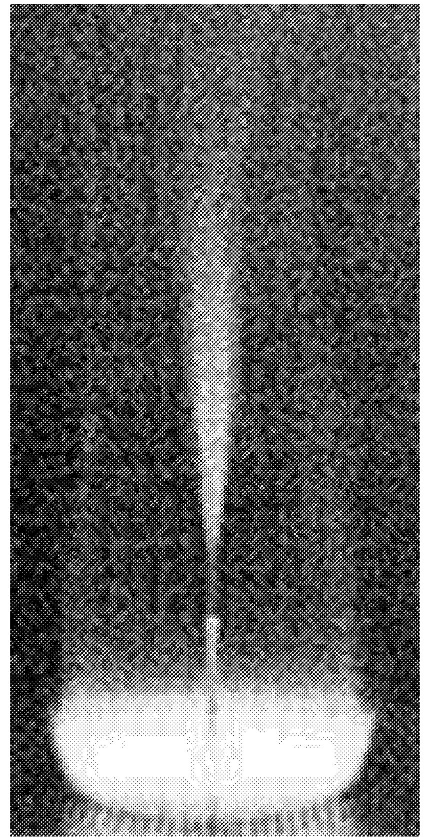
Jets in Rich Coflow



Air



Lean

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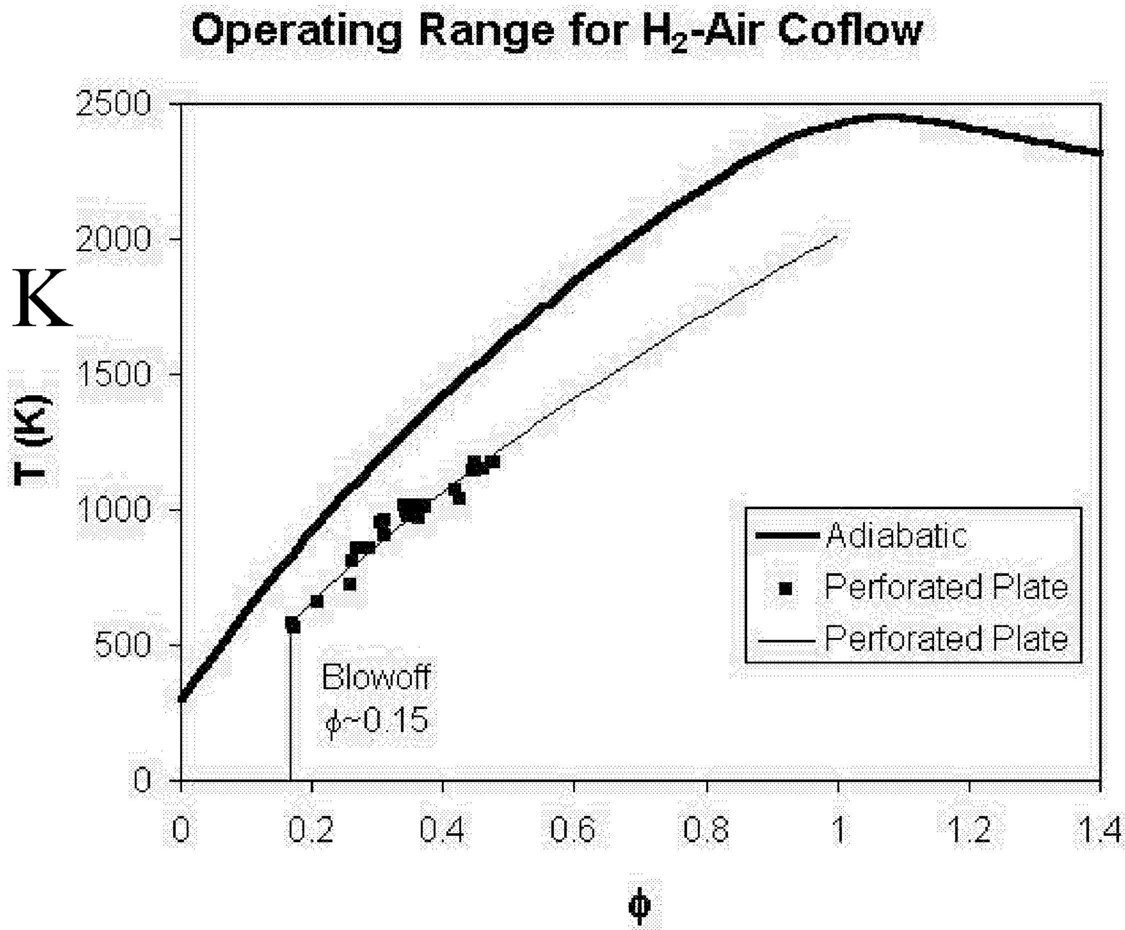
Operating Range for H_2 Coflow

Hydrogen-Air

- $\phi = [0.15,0.45]$
- T = [550,1200] K
- Upper limit unknown



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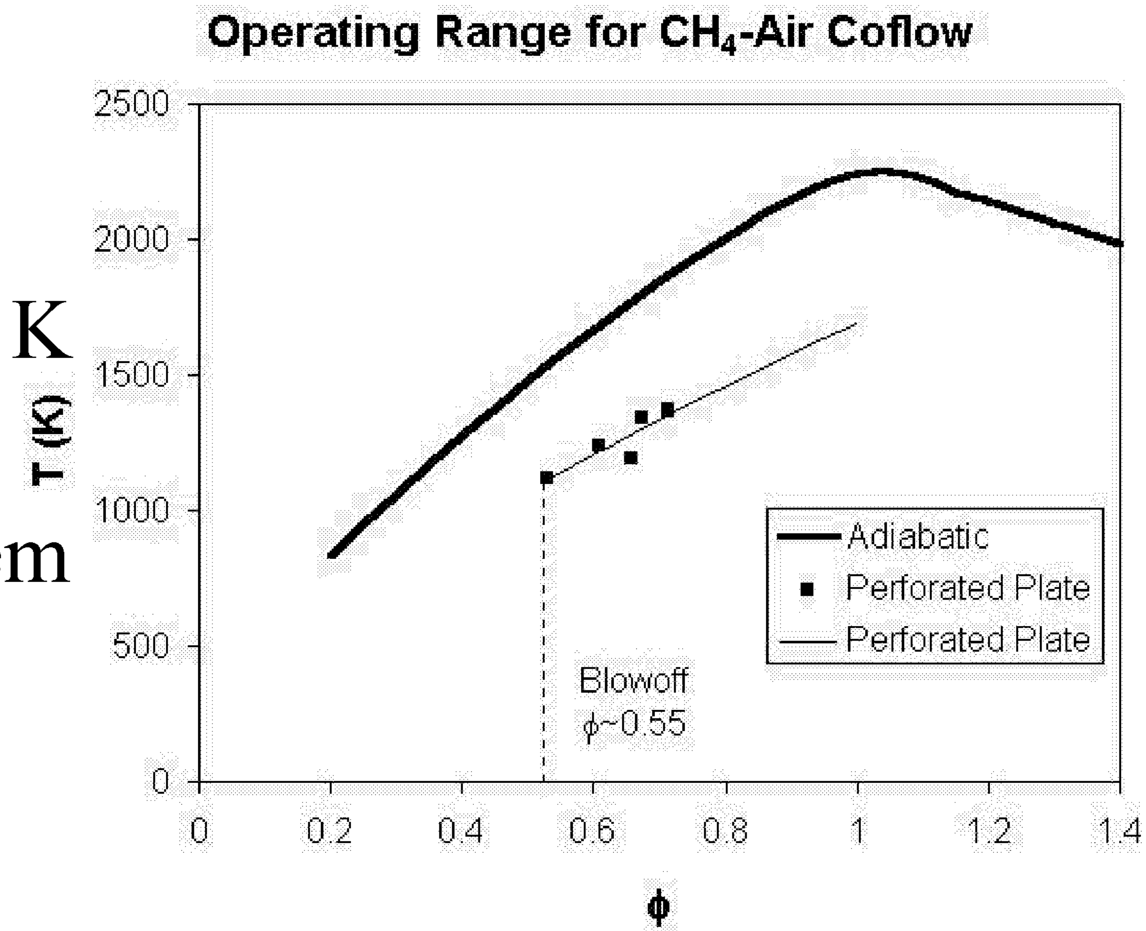
Operating Range for CH_4 Coflow

Methane-Air

- $\phi = [0.55, 0.7]$
- $T = [1100, 1400]$ K
- $\phi = 0.7$, too hot for exhaust system



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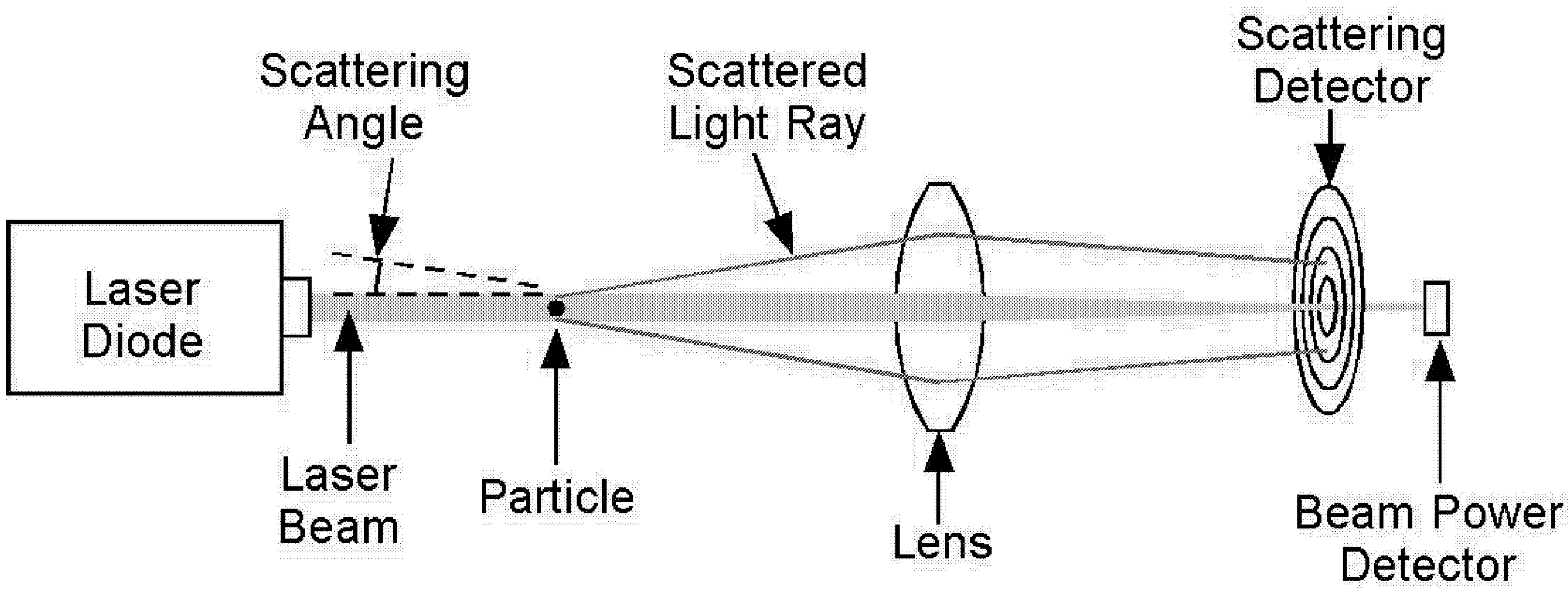
ELD Optical System



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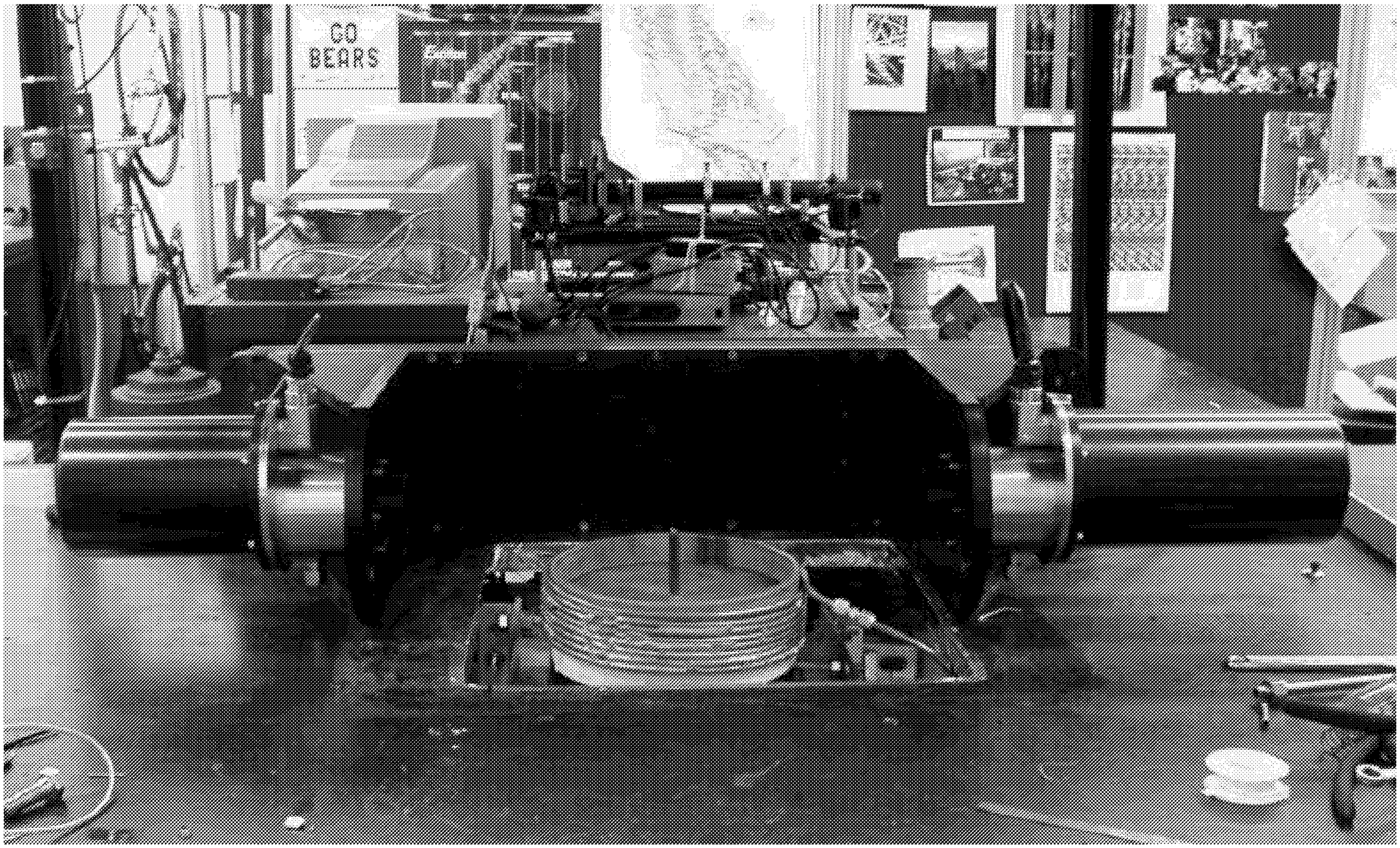
Malvern/INSITEC EPCS



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Ensemble Diffraction Measurements

- Ring detectors measure scattering signal $S(\theta_i)$ & transmission T.
- Determine droplet size distribution $V(d_i)$
- Determine the volume concentration C_V

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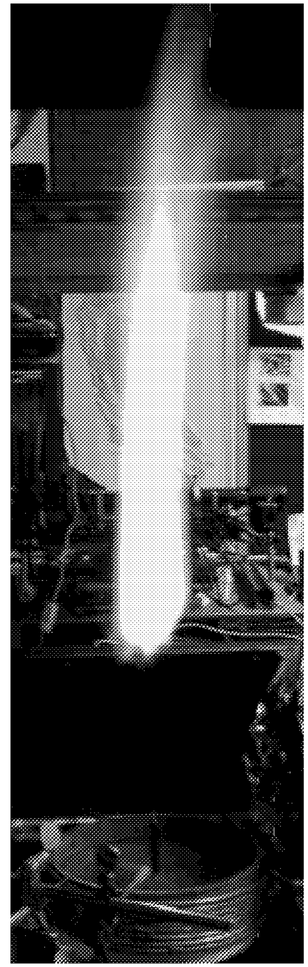
Methanol Spray Flame

- *Delavan* fuel nozzle
- FN: 0.7
- Spray angle: 45°
- Nozzle pressure: 35psi
- Methanol flow rate: 0.5 g/s
- Coflow ϕ: 0.3, T: 955K
- Coflow flow rate: 40 g/s, 1 m/s



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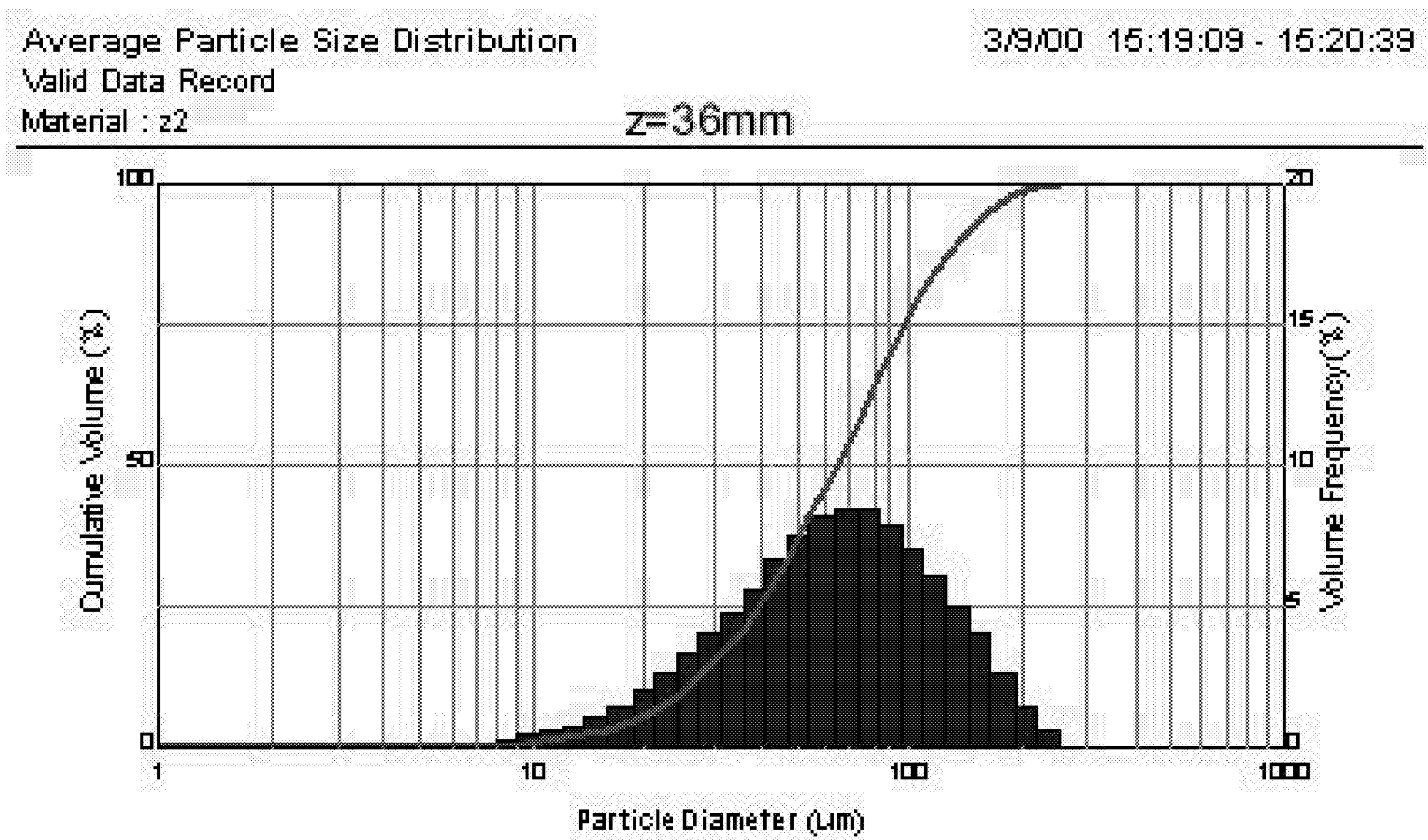
Droplet Size Distributions



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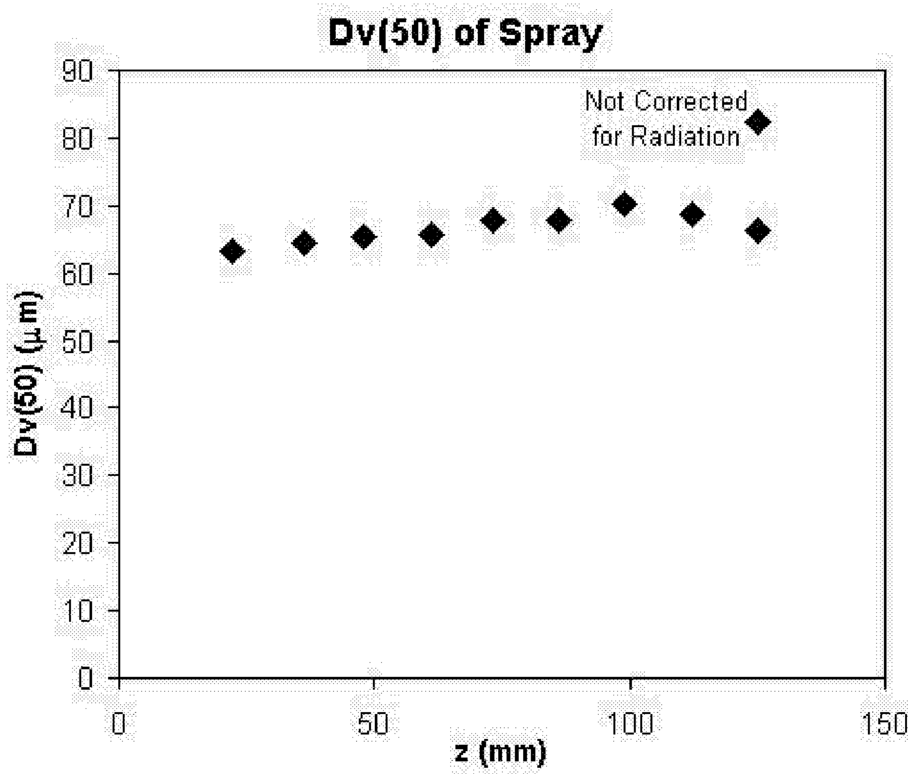
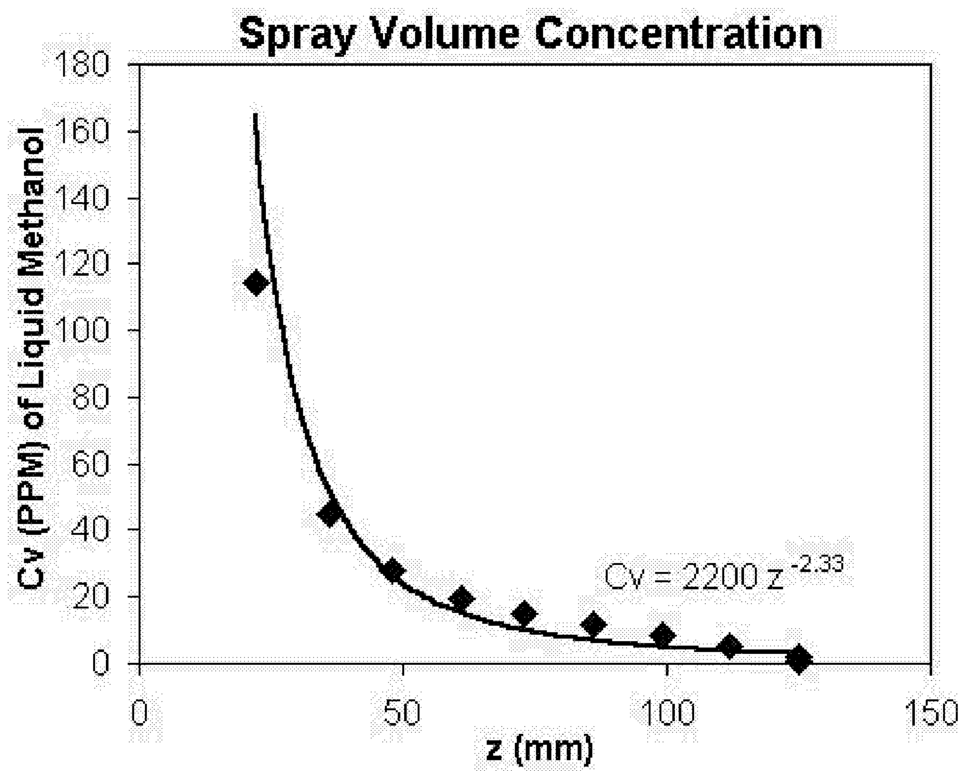
No Effect on Droplets





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No Effect on Droplets Before Flame

- The droplets diameters did not change until the flame front.
- Increase in coflow ϕ changes the vertical position of the flame front.

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Conclusions

- Coflow burner is proving to be a reliable, robust burner with a large operating range.
- Small to no changes in droplet size prior to flame front.
- More experiments are needed to confirm these results.

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What's Next?

- Continue to look at different nozzle flow rates and fuels.
- Global emission index ($CO\&CO_2:NO_X$) measurements.
- Laser diagnostics of gaseous jet at Sandia National Laboratories' Combustion Research Facility.

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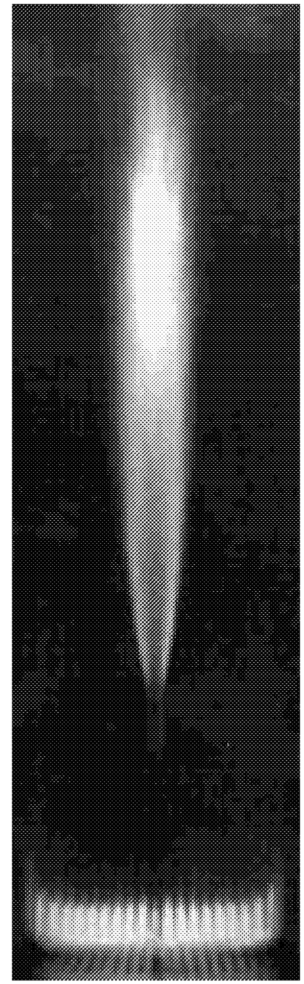
Vitiated Coflow Combustor



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Addendum (post-presentation)

The report was presented at the Combustion Institute's Western States Spring 2000 Meeting. The meeting was held on March 13-14 at the Colorado School of Mines in Golden, Colorado. Issues were raised during other presentations as well as during the question and answer period that prompted further investigations and this addendum.

As presented in the report, the mean droplet size was rather uniform between the nozzle and the flame front. For those analyses, the 50% volume diameter was used. It is a widely preferred practice to use the sauter mean diameter rather than the 50% volume diameter since it does not give extra weight to the larger droplets. Given this, the droplet size history of the spray shown below in Figure 1 is much different than what was presented.

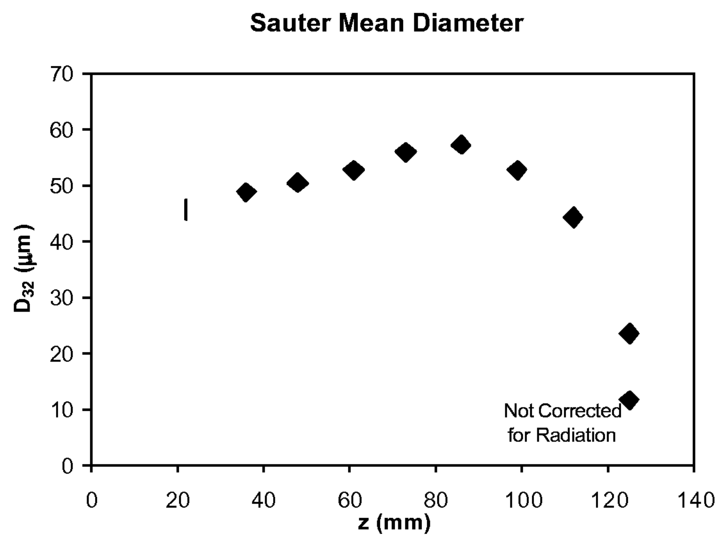

Figure 1.
Sauter mean diameter evolution (*Fuel:* Methanol, 0.5 g/s *Coflow:* H_2-Air, 40 g/s, ϕ:0.3, T:955K).

The trend in Figure 1 is in agreement with the results from other droplet research. Mean droplet sizes should increase due to the boiling off of smaller droplets. Finally, there is a drop off due to the complete combustion of the spray at 120 mm. Both the corrected and not corrected data are presented.

Questions arose concerning the resolution and accuracy of our measurements. The resolution of the system is limited by the size of the laser beam. As can be seen above in Figure 1, the resolution seems to be adequate given the fact that the droplet diameter is measured at about 20 μm at the flame front. The fact that only one laser is used in these scattering experiments may also effect accuracy. Calibration of our optical system and care to keep the spray as close as possible to the lens help minimize errors in the measurements.

The volume concentration was determined with the optical path of the beam centerline as estimated with the manufacturer specified spray angle. A presentation given on diesel sprays showed that the simultaneous use of two lasers offers the capability to measure the optical path and therefore get a more accurate measure of the volume concentration.

Let it be stated here that the main focus of our work at Berkeley is to investigate gaseous jet flames in a vitiated coflow. It is the intent of the presented research to get preliminary, quick measurements of a spray flame. We hope that this will spark interest in the use of our burner for spray research here as it has already done so in Germany and Japan. A group in Germany is currently building a copy of this burner to be used for spray research.

Ricardo Cabra
3/20/2000

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13. ABSTRACT *(Maximum 200 words)*

An experimental investigation is presented of a novel vitiated coflow spray flame burner. The vitiated coflow emulates the recirculation region of most combustors, such as gas turbines or furnaces; additionally, since the vitiated gases are coflowing, the burner allows exploration of the chemistry of recirculation without the corresponding fluid mechanics of recirculation. As such, this burner allows for chemical kinetic model development without obscurations caused by fluid mechanics. The burner consists of a central fuel jet (droplet or gaseous) surrounded by the oxygen rich combustion products of a lean premixed flame that is stabilized on a perforated, brass plate. The design presented allows for the reacting coflow to span a large range of temperatures and oxygen concentrations. Several experiments measuring the relationships between mixture stoichiometry and flame temperature are used to map out the operating ranges of the coflow burner. These include temperatures as low 300 °C to stoichiometric and oxygen concentrations from 18 percent to zero. This is achieved by stabilizing hydrogen-air premixed flames on a perforated plate. Furthermore, all of the CO_2 generated is from the jet combustion. Thus, a probe sample of NO_X and CO_2 yields uniquely an emission index, as is commonly done in gas turbine engine exhaust research. The ability to adjust the oxygen content of the coflow allows us to steadily increase the coflow temperature surrounding the jet. At some temperature, the jet ignites far downstream from the injector tube. Further increases in the coflow temperature results in autoignition occurring closer to the nozzle. Examples are given of methane jetting into a coflow that is lean, stoichiometric, and even rich. Furthermore, an air jet with a rich coflow produced a normal looking flame that is actually 'inverted' (air on the inside, surrounded by fuel). In the special case of spray injection, we demonstrate the efficacy of this novel burner with a methanol spray in a vitiated coflow. As a proof of concept, an ensemble light diffraction (ELD) optical instrument was used to conduct preliminary measurements of droplet size distribution and liquid volume fraction.

14. SUBJECT TERMS

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