Spray Drop Size and Velocity Measurements in a Swirl-Stabilized Combustor

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ABSTRACT

A pressure-swirl fuel nozzle generating a hollow-cone spray with nominal cone angle of 30 degrees is used in a swirl-stabilized combustor. The combustor is circular in cross section with swirl plate and fuel nozzle axes aligned and coinciding with the axis of the chamber. Kerosene is injected upward inside the chamber from the fuel nozzle. Separate swirl and dilution air flows are uniformly distributed into the chamber that pass through the honeycomb flow straighteners and screens. Calculated swirl number of 1.5 is generated with the design swirl plate exit air velocity of 30 degrees with respect to the chamber axis. Effects of swirl and dilution air flow rates on the shape and stability of the flame are investigated. Stable and classical liquid fuel sheet disintegration zone exists close to the nozzle with no visible light followed by a luminous blue region and a mixed blue/yellow region that subsequently turns into yellow for most of the part in the flame. A Phase Doppler Particle Analyzer (PDPA) is used to measure drop size, mean and rms axial velocity for two cases of with and without combustion at six different axial locations from the nozzle. For the non-combustion case all air and fuel flow rates were kept at the same values as the combusting spray condition. Results for mean axial drop velocity profiles indicate widening of the spray due to combustion while the magnitudes of the peak velocities are slightly increased. No measurements inside the hollow-cone spray are possible due to burning of fuel droplets. Drop turbulence decreases due to combination of increase in gas kinematic viscosity and elimination of small drops at high temperatures. Sauter Mean Diameter (SMD) radial profiles at all axial locations increase with combustion due to preferential burning of small drops.

INTRODUCTION

Spray combustion is of central importance from practical, theoretical, and computational points of view. The ultimate objective is the complete understanding of important processes in spray combustion to assist in designing a more fuel efficient and less environmentally destructive power generation/conversion devices. Gas turbine engines, liquid rockets, furnaces, incinerators, and diesel engines are typical examples in which spray combustion is of prime interest. In the following a short review of relevant works is presented for completeness prior to objectives of this work. This review is not meant to be extensive but to summarize the representative experimental efforts towards better understanding of spray combustion mainly of relevance to gas turbines and furnaces.

Onuma and Ogasawara (1975) studied the combustion of kerosene from an air atomizing type nozzle using a thermocouple for gas temperature with suction pyrometer (for radiation and conduction correction), pitot probe for gas flow velocity, a mechanical probe consisting of a small glass plate coated with magnesium oxide and a shutter mechanism for drop size and mass flux measurements, and finally a water-cooled stainless steel sampling probe connected to a gas chromatograph for species concentration measurements. They concluded that most of the fuel vapor from the drops formed a cloud that diffused towards the high temperature zone near the outer boundary of the flame. The fuel vapor was then decomposed into lower hydrocarbons which was subsequently oxidized to CO2 and H2O. Based on this they inferred that most of the droplets did not burn individually, but the vapor cloud from droplets burned as a diffusion flame in turbulent flow. This conclusion was also backed by similarities observed on the results obtained when propane (gaseous fuel) and kerosene were separately used through the same fuel nozzle. In a follow-up work Onuma et al. (1977) used the same set-up and measured NO distribution in heavy oil and kerosene. Based on similar behavior in two flames they supported their earlier conclusions.

Mitzotani et al. (1977) used kerosene injected by a pressure atomizer located on the axis at the exit of a convergent nozzle. Fuel had moderate swirl to
prevent recirculation in the spray. The air in the convergent nozzle was heated to investigate flame stabilization by a high temperature stream. A thermocouple, an impact probe, and a liquid-vapor phase-discriminating water-cooled sampling probe were used for gas temperature, gas velocity, and species concentration measurements respectively. Based on the results from sampling probe traverse through the flame, measuring fuel droplet flow and mass fraction of low molecular weight hydrocarbon (HC) gas, they concluded the followings: Initial spray evaporation entrains the surrounding high temperature air and, the fuel vapor thus produced is thermally cracked into low molecular weight HC. The flame burning velocity increases as mixture reaches the stoichiometric value and the flame front stabilized at a position where the burning velocity is balanced with the local flow velocity. Since the highest burning velocity was observed where the vapor and droplets of HC coexisted they stated that the fuel droplets should play a role other than that of vapor source in the process. Finally flame distance to the nozzle was much closer than the one calculated based on ignition delay mechanism. Thus concluding that this distance is established by flame propagation mechanism.

Khallal and Whitelaw (1977) used a single-component Laser Doppler Velocimeter (LDV) and time-constant-compensated thermocouples in an open flame fueled by an air-assisted pressure-swirl nozzle. No frequency shifting was used in the LDV and as such results were somewhat biased. Results along the centerline of (axial direction) kerosene flame showed that the maximum drop velocity and gas temperature fluctuations occurred at about the inflection points of their mean value axial profiles. Significant shortening of the flame length was observed as atomization parameters were changed to produce finer droplets. The droplet size distribution in the spray flame was not measured. Effects of air swirl for spray flame stabilization were investigated by Khallal et al. (1977) using an axisymmetric swirl stabilized combustor with a pressure--swirl nozzle. From the results obtained by pilot probe and thermocouple they detected a central recirculation zone within the spray which had a radial extent of 0.6 times the burner diameter and remained unchanged when swirl number was increased. However the axial extent increased with swirl and eventually became an open-ended recirculation zone.

Droplet size distribution produced by the nozzle can change the flame extent and perhaps its structure. Styles and Chigier (1977) measured drop size distribution in a non-burning spray from an air assisted atomizer. This atomizer was installed in the center of a disc shape bluff body for flame stabilization. A single-component frequency-shifted LDV, a coated unshielded Thermocouple with suction pyrometer, and a quartz sampling microprobe with gas chromatograph were used as diagnostic tools. They observed that drop velocities in the burning spray were higher than the non-burning case due to changes in phase resulting in increase in volume and changes in temperature causing increase in volumetric flow rate. The lateral expansion of spray flame was also detected. Owen (1978) and Owen et al. (1979) used Iso-Octane and No. 2 oil fuel sprays generated by a pressure-vapor atomizer in a center of an air swirler installed in a pipe to simulate part of the gas turbine combustion chamber. A one-component frequency-shifted LDV, conduction and radiation corrected thermocouples, and a liquid--vapor phase-discriminating sampling probe were used. The air was seeded to differentiate between drop and gas velocity. Detection of distinct bimodal velocity probability distribution function (pdf) when seeded was used and the separation of using drop-only pdf enabled them to decouple the gas from drop velocities at some locations. It was found that a toroidal reaction region length, as indicated by temperature contours within the spray, increased axially with significant decrease in centerline fuel vapor fraction as swirl number was increased. This is due to the reduction in fuel droplet penetration into the air stream, resulting in relative high centerline fuel concentrations. A toroidal external recirculation zone was observed to move closer to the swirl plate with increase in swirl number. Significant differences between mean gas and mean drop velocities were observed close to the nozzle. A significant part of the total unburned HC close to the nozzle on the centerline was liquid phase which was interpreted as coming from the main spray by entrainment.

Allen and Hanson (1986) using an intensified diode array camera looked at the planar images of OH laser-induced fluorescence to monitor multi-photon dissociation of C2H2 in an air-atomizing type nozzle. By examining large number of images they concluded that group combustion of drops was the predominant mode in spray. Single droplet combustion might be more likely to occur at the edges of the flame where droplet momentum carries individual droplets into oxygen-rich regions. De La Rosa et al (1986) analyzed dropsize distributions in a non-burning spray for an air-blast atomizer using a Laser diffraction particle analyzer. Two oil fuels, No. 2 and No. 6, were used with the same atomization parameters. The heavier fuel (No. 6) showed larger drops and burned very differently. Many drops appeared, in photographs, to burn individually and many were quenched before complete burning. The difference in flame characteristics are attributed to the different dropsize and velocity distributions and their evaporation history. However drop size and velocity distributions were not measured in the burning spray.

McDonell et al (1986) used JP-4 fuel in an air-assist atomizer installed in a swirl-stabilized combustor with wall-jacketed dilution air. The atomizer was installed in a separate rig injecting downward for cold flow studies and the results were compared with those of burning spray in the aforementioned combustor. As such the coupled effects of the air swirl and combustion were investigated. A Phase Doppler Particle Analyzer (PDPA), Bachalo (1980), for dropsize and velocity in both burning and nonburning, a Laser diffraction particle analyzer for cold flow only, and thermocouples were employed as diagnostic tools. No on-axis recirculation zone was observed close to the nozzle. However, away from the spray axis, recirculation zone was detected due to interaction of fuel spray and the surrounding swirling air. Radial profiles of Sauter Mean Diameter (SMD) at several axial locations for both cold and burning sprays have been measured. A minimum value on the axis which increased in average size as one moved radially outward. Lower SMD values for burning case were observed around the edge of the spray. This and the observed radial widening of the burning spray were thought to be due to the outward radial momentum imparted to the spray by the
Although considerable progress has been made towards understanding of spray combustion theoretically, experimentally, and computationally in the past ten years we are still far from a coherent and complete understanding of this subject. The objective of this paper is to report preliminary results taken from a spray with and without combustion in the same combustor and with identical boundary and initial conditions to investigate effects of combustion on the flow field and spray characteristics.

**EXPERIMENTAL SETUP AND INSTRUMENTATION**

Figure 1 shows a schematic drawing of the combustor. The combustor consists of a circular cross section stainless steel pipe of 265 mm in diameter and 768 mm in total length which is positioned in vertical direction. An internal pipe of 98 mm in diameter and 254 mm in length, through which swirl air flows, is installed at the lower end of (and concentric with) the outer pipe. The main air from the compressor goes through regulator/filter assembly and is divided into two branches, one for dilution air and the other for swirl air. Air in each branch passes through a regulator, a valve, and a rotameter to a manifold from which four pipes are drawn to the lower end plate of the combustor for uniform air distribution. Each pipe ends into a specially designed distributor inside the combustor to spread the air evenly in all directions. A distance of about 102 mm from the end plate to the lower face of the honey comb was found to be sufficient to allow proper and uniform air distribution inside the combustor. Fuel from the tank passes through filters and is pumped into an on-axis vertically-adjustable tube after passing through a rotameter for fuel flow rate measurements. Bell Super K-1 kerosene is used for all experiments and was ignited via a small sidewall opening with a propane torch, which is subsequently removed. A Delavan industrial type pressure-swirl nozzle producing a hollow-cone spray with nominal total spray cone angle of 30° and rated flow rate of 38.5 ± 0.99 cc/min (fuel density of 0.8 gr/cc) is used at the end of the fuel tube in the combustor. An air swirl plate is installed flush with upper edge of the swirl pipe. Looking into the swirl plate one sees ten radial slots of 32.5 mm in length and 5.5 mm in width equally spaced tangentially. These slots generate a calculated swirl number of about 1.5 with the design exit velocity of 30° with respect to the chamber axis, Gupta et al. (1984). The swirl plate thickness of 19 mm is sufficient for proper flow direction. Three 514 mm X 108 mm semi-conductor grade high temperature fused quartz glasses are installed for optical access into the combustor. Two of the windows are at 90° with each other with the third being at 150° from one of the them. This is required due to optimized operating arrangement of our Laser instrumentation. A special thin combustor sleeve is designed to cover and protect unwanted window areas from fouling. This also provides a recess-free combustor interior surfaces.

A single-component Phase Doppler Particle Analyzer (PDPA) model no. XMT-1100 (Optical Transmitter), RCV 2100 (Optical Receiver) was used to measure size and velocity of each individual drop simultaneously. Both receiving and transmitting optics were rigidly mounted on a three dimensional traversing machine with one digital readout for each direction. Receiving and transmitting lenses were 495...
mm f.l. with f/no. 4.7 and 495 f.l. with f/no. 7 respectively. Collimating Lens with 300 f.l. and slit width of 100 µm were used in receiving optics. Mean gas temperature was measured using a Pt-PtRh (13%) type R thermocouple. Thermocouple wires were thermally insulated from its 1.57 mm-diameter stem using an insulating paste. Photographs of the flame were taken using black and white ASA 400 film in a Nikon 35mm camera with Vivitar zoom lens. A CCD Sony Video Camera was employed to document the flame behavior with changes in both design and operating conditions.

RESULTS AND DISCUSSIONS

With a fixed fuel atomizer parameters and a given swirl plate design there are basically two main inputs, dilution and swirl airflows, that can be varied at fixed inlet air and fuel temperatures. The behavior of the flame has been studied by photography and video camera to characterize the stable operating conditions of the combustor. Figure 2 shows boundaries beyond which flame cannot exist. In the following a pair number of 1.98/1.13 implies swirl flow rate of 1.98 m³/min and dilution of 1.13 m³/min. At a fixed dilution air of, for example, 1.13 m³/min, the most stable flame was found to exist around 1.95/1.13 (square symbol in Fig. 2). As the swirl was increased at constant dilution air, the average flame tip height gradually decreased from 102 mm to a fixed value of about 76 mm at 2.26/1.13 m³/min, see Fig. 3. Further increase in swirl air flow rate did not change the flame structure until close to 2.69 m³/min where the flame was suddenly extinguished. However, the behavior of the flame was completely different when swirl air flow rate was decreased at a constant dilution air flow rate. The average flame tip height increased rapidly, flame became more sooty and luminous, and stayed stable until swirl air of about 1.36 m³/min. At about this swirl air value the flame lifted up, became unstable, and was eventually blown out of the combustor. This behavior was observed at the lower boundary of the curve in Fig. 2 for all dilution air of less than about 2.12 m³/min. The flame response at all points in the upper curve of this figure, however, was similar for all dilution flow rates. The dashed line region showed bimodal behavior, flipping from upper or lower boundary flame types. All experimental results from PDPA and thermocouple were taken at 1.98/1.13 condition. Moving from 1.98/1.13 point to the right along a horizontal direction in Figure 2 did not show significant change in flame length until at dilution air of about 2.83 m³/min where the flame was
extinguished. Lowering the dilution, however, changed the flame shape. It opened up and bowed towards the combustor walls.

Figure 4 presents photographs taken at a fixed dilution air of 1.13 m/min for various swirl air flow rates. These photographs were taken with exposure time of 1/60 sec. with f/no. aperture of 5.6. Close examination of the color photos (not shown here) at 1.98/1.13 condition showed several regions of the spray flame. Very close to the nozzle a conical liquid sheet exists that disintegrates into droplets. This region is up to about 10 mm above the nozzle. From 10 mm to about 30 mm the time averaged color photos show exclusively light-blue region surrounded by spray droplets made visible by laser light. From 20 mm to 35 mm mixture of blue and yellow colors is seen with exclusively yellowish flame above 35 mm. The average flame tip height was about 100 mm at 1.98/1.13 condition. The short exposure (1/3000 sec.) photos, however, revealed completely different view than the long time averaged ones. They show nonuniformly-distributed, separated and/or connected regions of visible flame that apparently expand and/or are extinguished and move around rapidly so that on the averages flame appears like those in Fig. 4.

Figure 5 and 6 present results of parametric studies of the instrument variables of PDPA. Chehroudi (1990) and Bachalo (1988) showed changes in some of the results obtained by PDPA in sprays if “optimum and/or proper” choices of these instrument variables were not made, particularly, in the dense region of sprays. Therefore, prior to final data acquisition two representative radial locations, one inside and the other outside the flame, were chosen at axial position of 15 mm from the nozzle for parametric study. Rejection rate for the data in this study was at most 20 percent. Effects of photomultiplier (PM) tube voltage on the indicated measured quantities.

Figure 7 shows radial profiles of mean drop axial velocity with and without combustion at six different axial locations. Rejection rate for these data is at most 20 percent and in addition beam steering was visually observed not to be significant. At each measured axial position a horizontal line is drawn to show the zero mean velocity and temperature levels. Two inner up-going diverging lines represent the extent of spray if it penetrated at nominal spray initial angle. Two outer diverging curves show the outer edge of the visible flame brush zone taken from the photographs of Fig. 4. The measurement volume traverse direction was from right to left in this figure, and hence results to the right of the center line is more reliable due to minimum spray and/or flame interference. Data for only axial locations of 70 and 90 mm are mirror imaged with respect to the center line for visual aid. Mean drop velocity profiles for the non-burning case show a typical double hump profile which was also observed by others in hollow-cone sprays, for example see Bachalo and Houck (1986) and McVey et al. (1989). Negative mean velocity is seen to exist around the spray center line axis for axial locations of larger than 25 mm indicating existence of a toroidal recirculation zone.
velocity with combustion. This is due to enhancement 
vertical line one can observe higher mean drop axial 
horizontally shifted to align the peaks along a 
downward movement of the recirculation zone. 
Strictly, this cannot be confirmed unless flow is 
separated for gas and liquid within the spray 
flame at all axial locations. At 15 mm the peak of 
the mean velocity profile for the nonburning case 
very close to the nominal spray angle which later 
leaves from it away from the nozzle. This is due to 
the swirling air and turbulent diffusion. 

Figure 6 is plots of rms of drop velocity 
fluctuations using the same format of Fig. 7. For the 
nonburning case they show local minimum at the center 
line above 15 mm axial position with peaks at about 
inflection points of the corresponding mean drop 
velocity profiles of Fig. 7. The only appreciable 
difference between results with and without combustion 
occurs in the outer region of spray. However if the 
profiles are horizontally shifted such that the peaks 
of their corresponding mean velocity profiles align, 
then the rms of drop velocity fluctuations for 
burning case will always be lower than the isoenthalpic 
one. This lower value is perhaps due to evaporation 
of small drops (Fig. 9) and increase in gas kinematic 
viscosity at high temperatures. 

Figure 9 shows the SMD profiles with and without 
combustion. Horizontal line at each axial position 
represents base SMD of 20 microns. SMD radial 
profiles with combustion show increase in almost all 
locations due to preferential evaporation of small 
drops (d^2-law) that shift the probability distribution 
function of drop sizes towards the larger drops. For the 
isoenthalpic case they portray the classical double 
jump profile with large drops close to the spray 
nominal spray angle surrounded by deflected small 
drops. 

Average temperatures were also measured and 
their profiles are shown as dashed lines in Figs. 7, 
8, 9. Except at 15 mm from the nozzle they increase 
gradually reaching a maximum and decline to a minimum 
on the axis due to dilution with extra air and 
radiation losses. Using mean drop velocity profiles 
of Fig. 7 and the photographs of the flames, three 
radial zones are realized at most axial positions (see 
Fig. 7). Preheat/reaction zone covers from the outer 
edge of the visible flame brush radially outward to 
the edge of the spray (where mean drop velocity 
measurements are possible). Turbulent flame-brush 
zone from the peak of the mean temperature profile to 
this outer edge of the flame. Finally burned gases 
zone inside the spray flame where toroidal 
recirculation exists. 

CONCLUSIONS 

Limits at which flame is either extinguished or 
blown off in a model swirl combustor were determined. 
At each fixed dilution air flow rate increasing the 
swirl flow eventually extinguished the flame, and 
decreasing it caused the flame to lift up and be blown 
out of the combustor. Based on photographs alone four 
distinct regions were determined: dense spray region 
with no visible light, blue region, mixed blue and 
yellow region, and exclusively yellow region. Effects 
of combustion on the spray was to increase the mean 
drop velocity, decrease the rms of drop velocity 
fluctuations, and to raise the SMD value. The spray 
was also widened by combustion. 

Radial profiles of 
average temperature were also measured indicating a 
peak and a minimum due to reversed flow at the center 
line. From average flame pictures and temperature 
profiles three radial zones were defined: 
Preheat/reaction zone, turbulent flame-brush zone, and 
burned gases zone.
Figure 7. Offset plots of the mean axial drop velocity with (solid symbol) and without (hollow symbols) combustion at six different axial locations. Dashed curve shows mean temperature profile.

Figure 8. Offset plots of the rms of the drop velocity fluctuations with (solid symbol) and without (hollow symbols) combustion at six different axial locations. Dashed curve shows mean temperature profile.

Figure 9. Offset plots of the SMD with (solid symbols) and without (hollow symbols) combustion at six different axial locations. Dashed curve shows mean temperature profile.

REFERENCES


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