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EXPERIMENTAL DIAGNOSTICS AND THEIR APPLICATIONS

A Laser Anemometer Seeding Technique for Combustion Flows with Multiple Stream Injection

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In nonpremixed combustion systems, fuel and oxidant are injected into the reaction chamber via two or more separate streams. Velocity measurements by laser anemometry within the chamber may be biased by individual streams unless the seeding concentrations of both streams are uniform and constant. In order to meet this requirement, a seeding technique has been developed to disperse 1- μ m metal oxide particles at a controllable rate. Evaluations of the steadiness of particle generation indicate rms fluctuations are within 1.5% of the particle generation rate. Demonstration of the technique has been conducted in both nonreacting and reacting flows.

1. INTRODUCTION

The advent of laser anemometry (LA) for the measurement of velocity in fluids has prompted a requirement for the generation of micron-sized light scattering particles. The particles are needed to track the flow and allow the local velocity to be measured by scattering light from a sampling volume comprised of laser induced interferometric fringes. The instantaneous velocity of the particle (hence the flow velocity) is derived from the frequency of the light scattered from the fringes.

Signal quality and accuracy of the velocity measurement are dependent upon the properties of the seeds generated. The criteria important in the performance of a particle generator include

- (1) generation of monodispersed particles with good light scattering characteristics,
- (2) generation of a steady flux of particles, generation of a particle size sufficiently small to track the fluid flow, and
- (3) control over the rate of particle generation.

Seeding methods such as atomization of low-volatile liquids [1], particle suspensions [2], or

solutions which subsequently dry and form crystalline solids [3] have been successfully used in nonreacting flows. Combusting flows, however, require the use of refractory particles, such as metal oxides, that can survive the hostile environment and not appreciably perturb the local flow. Fluidized beds are usually employed to accomplish this objective [4, 5], but their performance is less than desirable due to large fluctuations in particle output [6], and lack of control over the rate of particle generation. This deficiency is especially troublesome in most combustion systems wherein flows from more than one stream (e.g., fuel stream and oxidant stream) enter the chamber. In these cases, the steadiness of particle generation in each stream, and the ability to vary the rate of seed particle generation to insure uniformity of seed concentration among the streams are crucial if biasing of the velocity data by one stream is to be prevented.

The present study addressed the development of a seed generation technique for combusting flows, and the evaluation of its performance in providing both a steady rate of injection and a uniform volumetric seed concentration for a combustion chamber featuring multiple stream injection.

Fig. 1. Seeding system.

2. PARTICLE GENERATOR

The particle generation seeding system is schematically depicted in Fig. 1. Air is delivered at line pressure (~ 60 psig) to a dryer (Wilkerson Model X03-02-000) for the removal of residual moisture. The air is then channeled through a high-quality filter (Balston DQ Grade), capable of 90% retention of $0.6 \mu\text{m}$, to remove undesirable residue. The air pressure is regulated (Norgren Type R-11),

usually 20-30 psig, to provide atomization conditions specified by the atomizer (RETEC X70). The atomization air and the secondary air are metered by rotameters (DWYER Models RMB-51 and RMB-54), ordinary in 10:1 secondary to atomization air proportions. A suspension of metal oxide (aluminum oxide, Al_2O_3 , in the present case) and deionized water is agitated by a magnetic stirrer to provide a uniformly mixed suspension. The suspension is mixed in proportions, usually

Fig. 2. Combustor configuration.

Fig. 3. Scanning electron micrographs (SEM) of seed particles.

4 g/l, that minimize the probability of having multiple particles per drop. The atomizer produces an aerosol with a mass median diameter (MMD) of $5.1 \mu\text{m}$ with a geometric standard deviation of $2 \mu\text{m}$. After atomization, the aerosol is carried to a mixing chamber. The secondary air is injected tangentially into the mixing chamber to induce mixing and decrease the humidity of the seeded flow. The capability of charge neutralizing the aerosol is also provided by passing the aerosol through a radiation flux produced by a 10-mC vial of Krypton-85 gas (3M Model 3B4G).

3. SYSTEM EVALUATION

Combustor

In the present experiments, a nonpremixed combustion chamber was selected to test the system for multiple stream injection. The combustor has a centerbody configuration as shown in Fig. 2. The 51-mm-i.d. combustor tube houses a 30.5-mm-o.d. centerbody around which the annular air jet can be swirled. A 1.3-mm-i.d. fuel jet is located in the center of the centerbody face.

Particles

Light scattering refractory particles of sufficient size to provide adequate light but small enough to

follow the flow are required for laser measurements. Melling and Whitelaw [7] found that $1.3 \mu\text{m}$ and $0.4 \mu\text{m}$ titanium dioxide (TiO_2) spherical particles in air would follow 1- and 10-kHz turbulent fluctuations respectively to within 1%. Thus, $1.0\text{-}\mu\text{m}$ -diam Al_2O_3 particles were selected for the present case to provide adequate scattering and representation of fluid velocity.

Al_2O_3 particles nominally sized at $1.0 \mu\text{m}$ and $1.5 \mu\text{m}$ were used. The actual size of generated particles was determined by a scanning electron microscope (SEM). The micrographs (Fig. 3a) show that the nominal $1.0 \mu\text{m}$ amorphous Al_2O_3 particles were substantially smaller, approximately $0.1 \mu\text{m}$, than the quoted size. The $1.5\text{-}\mu\text{m}$ crystalline Al_2O_3 generated particles were approximately $1.0 \mu\text{m}$ (Fig. 3b). The significant variation from the quoted size in the $1.0\text{-}\mu\text{m}$ Al_2O_3 case was due to the morphology of the Al_2O_3 . Amorphous Al_2O_3 is composed of agglomerations of $\sim 0.1\text{-}\mu\text{m}$ particles having an average agglomerated diameter of $1 \mu\text{m}$. Such agglomerations can be seen in Fig. 3a. When $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ suspensions are atomized and the moisture evaporated, the resultant particles are considerably smaller than the quoted size. In hot flow cases, the sudden heating breaks apart the remaining agglomerations that are of sufficient size to be useful, causing poor signal quality and data rate. Conversely, because of the

Fig. 4. Particle rate measurement system.

a) DEPENDENCE ON TIME

Fig. 5. Particle generation rate.

b) DEPENDENCE ON ATOMIZER DIFFERENTIAL PRESSURE

c) DEPENDENCE ON SUSPENSION CONCENTRATION

Fig. 5. (Continued).

crystalline structure of the $1.5\text{-}\mu\text{m}$ Al_2O_3 particles, there was little degradation in size due to either atomization or thermal effects.

Once it was determined that the $1.5\text{-}\mu\text{m}$ particles were to be used, a particle neutralizer was employed to assess the effect of neutralizing the charge of the aerosol. The particle neutralizer in the present tests had no significant effect on the size of the generated particle (Fig. 3c).

Particle Generator Performance

The particle generation rate was examined by utilizing the laser system shown in Fig. 4. A single beam (green, $514.5\text{ }\mu\text{m}$) of an argon ion laser was collimated, focused, and directed through the combustor test section. Light scattered by particles passing through the laser beam at the center of the duct was focused onto a 0.25-mm -diam aperture of a photomultiplier tube located at a 25° angle to the laser beam. The output of the photomultiplier was amplified and fed into a Schmitt Trigger which provided TTL level pulses to a frequency counter. The number of particles passing through the area of sensitivity was recorded in ten second intervals and scaled by the area ratio (18,000:1) of the test section to the

sensing area to obtain a total particle generation rate.

Particle generation rate data are presented in Fig. 5a for a period of time exceeding 1 h. Using a 4-g/l $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ suspension, 25-psig atomizer pressure, and 10:1 dilution ratio, the mean generation rate is 1.1×10^7 particles/s with rms fluctuations of 1.5%. This unsteadiness is a significant improvement over fluidized beds which have fluctuations of about 13% [4].

In order to match the volumetric concentration of independently seeded streams, a parametric variation on the atomization seeding system was conducted. The particle generation rate was recorded for two conditions: (1) fixed suspension concentration with varying differential pressures across the atomizer, and (2) fixed atomizer differential pressure with varying suspension concentrations. The generation rate was found to vary linearly with both atomizer differential pressure (Fig. 5b) and suspension concentration (Fig. 5c) for the operating conditions considered.

One question with respect to this technique of seed generation is the amount of moisture introduced by the atomization process. At a 10:1 dilution ratio, the relative humidity at the output of mixing chamber is about 50% at 72°F (0.8

Fig. 6. Laser anemometer system.

Fig. 7. Laser results.

weight percent of water). Since the aerosol is further diluted by an additional 10:1 when introduced into each stream entering the reactor, the presence of the moisture is considered negligible.

Particle Generator Demonstration

The performance of the seeding system was tested in practical application in both reacting (propane central jet, air annular jet) and nonreacting (CO_2 central jet, air annular jet) flows with and without 45° swirl, bulk velocities of 7.5 and 15.0 m/s, and variable equivalence ratios. A schematic of the argon ion laser anemometer system, used to obtain the velocity measurements, is shown in Fig. 6. A 40-MHz frequency shift was provided in order to resolve directional ambiguity.

Representative radial and axial profiles of axial velocity and turbulent intensity are presented in Fig. 7 for one set of run conditions (7.5 m/s, no swirl, $\phi = 0.05$), both reacting and nonreacting. Separate seeding systems were used for the mainstream air and jet fuel flow. The central jet seeding system operated at a higher pressure (30 psig) than the mainstream seeding system (25 psig), but with the same differential pressure across the atomizer. The volumetric seed particle concentration of both streams was matched by varying the concentration of the $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ suspension in the two jet seeders. In both cases, the data rate of validated scores was in excess of 500 events/sec and the signal quality was excellent with modest degradation in the reacting flow due to particle attrition in the regions of high temperature.

4. SUMMARY

A particle generation system has been designed and successfully employed to introduce seed in uniform concentration to flows typical of nonpremixed combustors that feature multiple stream injection. An assessment of the system performance resulted in the following observations:

- (1) Particle generation rates on the order of 10^7 particles/second can be produced at a steady rate over prolonged periods of time.
- (2) rms fluctuations of 1.5% in particle generation

rate are typical for operating periods in excess of one hour.

- (3) Particle generation rate is linearly dependent on (a) atomization differential pressure for fixed suspension concentration or (b) suspension concentration for a fixed atomizer differential pressure.
- (4) Crystalline rather than amorphous aluminum oxide is preferable to ensure control over the final size of the seed particulate.

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