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# Technical Notes

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## Measurements of Droplet Dispersion in Heated and Unheated Turbulent Jets

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### Introduction

THE dispersion and vaporization of individual droplets in a heated and unheated turbulent jet are studied. A steady stream of pentane or hexadecane droplets is generated using a piezoelectric transducer. They are injected along the centerline of the turbulent jet. Aspects of the experimental methodology are discussed elsewhere by Call and Kennedy.[1]

As the droplets travel axially downstream, they are displaced radially by the jet turbulence; the displacement from the jet axis is measured with a sheet of laser light and a position-sensitive photomultiplier tube (pmt). Axial droplet velocities are obtained using two, parallel sheets of laser light separated by several millimeters.

For the isothermal case, the air jet Reynolds number is 15,000 based on a nozzle diameter of 7 mm. The centerline velocity is 32 m $s^{-1}$ and the measured rms velocity is 0.05±0.02 m $s^{-1}$ across the nozzle exit. For the heated jet, the mass flow at the nozzle exit was kept constant. The air velocity is calculated to be 36.1 m $s^{-1}$ with a Reynolds number of 14,400 and an exit temperature of 60° C. The initial conditions are described more fully by Call and Kennedy.[2] Velocities were measured with a hot-wire anemometer, and temperatures with a cold wire. Profiles of mean axial velocities in the unheated jet and mean temperatures in the heated jet along the jet axis are shown in Fig. 1. The normalized rms fluctuations of velocity and temperature are also shown. The profiles are typical of fully developed turbulent jets;[3] the temperature in the heated jet is seen to behave, by its similarity to the normalized velocity profiles in the unheated jet, as a passive scalar. Therefore, the structure of the heated jet is expected to be very similar to the unheated jet.

Data are presented for hexadecane droplets with diameters of 90 μm and pentane droplets with diameters at the nozzle exit of 113–115 μm. The time constant of particle response is about 19 ms for the 90-μm hexadecane droplets. The estimated integral time scale for the unheated jet at $x_1/d = 40$ is about 18 ms which yields a typical turbulence Stokes number of around 1.

The hexadecane droplets do not experience significant vaporization during the course of the experiment. Droplet velocities were determined from time-of-flight measurements for the pentane and hexadecane droplets in the heated and unheated jets as a function of the axial distance from the jet nozzle. Corresponding measurements of the mean time of flight from the nozzle to some downstream axial plane show that the vaporizing droplets take longer to reach a given distance; as their diameter decreases, they adjust more readily to the slower gas flow. This effect should be partially negated by the decrease in drag that results from the vaporization

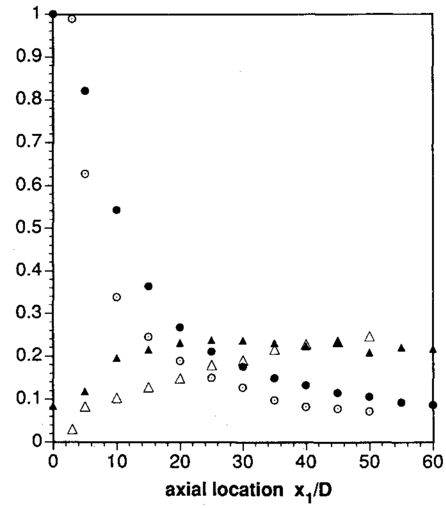


**Fig. 1 Axial centerline profiles. •: mean axial velocity in unheated jet normalized by exit velocity; o: mean temperature (relative to freestream temperature) in heated jet normalized by exit temperature difference; Δ: rms velocity normalized by local mean velocity; and Δ: rms temperature normalized by local mean temperature relative to freestream.**

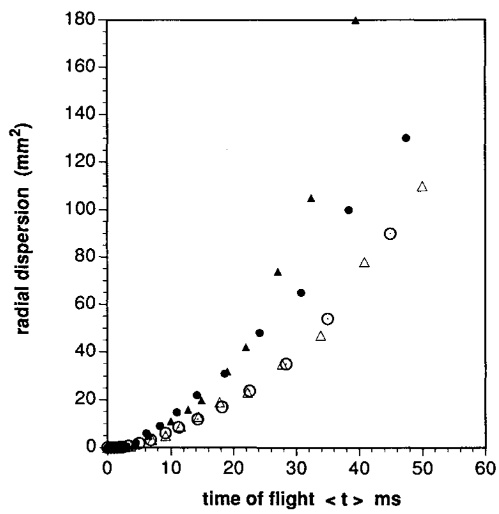


**Fig. 2 Dispersion in $x_2$ (radial) direction as a function of mean time of flight. Δ: pentane droplets in heated jet; •: hexadecane droplets in heated jet; Δ: pentane droplets in unheated jet; o: hexadecane droplets in unheated jet.**

but the data indicate that any effect of vaporization is small for these conditions.

Figure 2 shows the dispersion as a function of mean time of flight for the four data sets. The pentane droplets in the heated jet experience relatively rapid dispersion. Two opposing effects are at play under these conditions. The mass transfer or "blowing" from the pentane droplet surface will tend to reduce the drag. On the other hand, the loss of mass reduces the inertia of the droplets. This facilitates their dispersion. From a comparison of the results for the dispersion of pentane and hexadecane droplets in the heated jet, it may be concluded that the loss of mass overwhelms any im-

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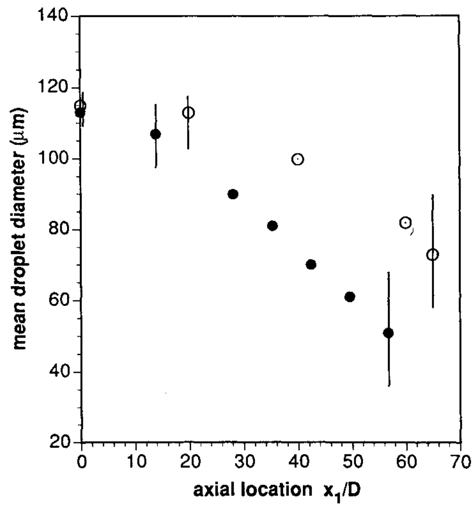


**Fig. 3 Pentane droplet diameter as a function of axial distance. Bars represent the scatter in the sampled droplet diameters. •: pentane in heated jet; and o: pentane in unheated jet.**

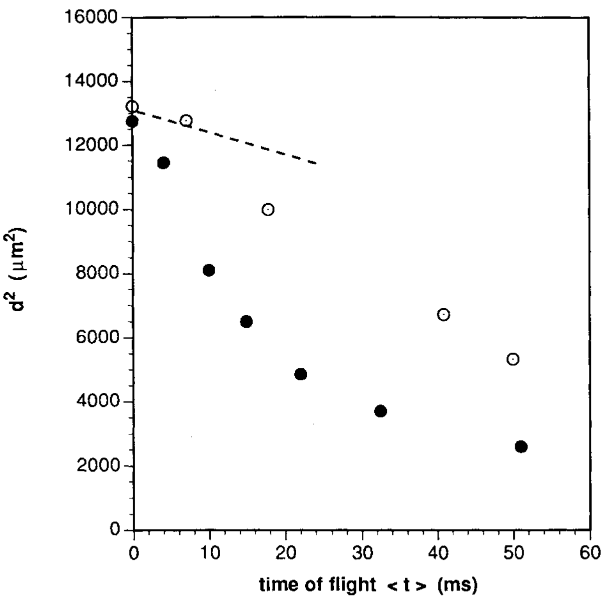


**Fig. 4 Pentane droplet diameter squared as a function of mean time of flight from the nozzle exit. Dashed line represents "$d^2$ law" behavior of a pentane droplet in air at 20° C. •: pentane in heated jet; and o: pentane in unheated jet.**

pact of vaporization on droplet drag. This conclusion will be pertinent to combusting sprays in particular.

Figure 3 shows the mean droplet diameter as a function of the axial distance. The droplet diameters were measured with a slide impaction technique. The bars represent the range of diameters which were measured and used to compute the mean diameters. Ten to twenty samples were used for each data point. The diameter data in Fig. 3 are replotted in Fig. 4 using the time-of-flight data. The dashed straight line represents the well-known "$d^2$ law" for a pentane droplet vaporizing in quiescent air at 20 °C. Because the jet mean temperature is continuously dropping, the pentane droplets in the heated jet experience a declining driving force for vaporization, and thus, do not follow the $d^2$ law. Call and Kennedy[2] have shown that stochastic simulations[4] do a poor job of reproducing the behavior of the vaporizing droplets. The results suggest that problems may exist with the modeling of droplet vaporization in a turbulent flow.

## Acknowledgment

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# Numerical Simulation of Acoustic Waves in a Combustor Using Total-Variation-Diminishing Schemes

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## Introduction

COMBUSTION instabilities in liquid and solid rocket engines are organized, large-amplitude unsteady motions of compressible gases coupled with oscillations of the combustion chamber pressure. They occur during steady state as well as during transient operations and result from complex, nonlinear interactions among acoustic waves and heat release processes. One of the major types of combustion instability for liquid-propellant engines is acoustic instability (sound wave amplification). They occur when driving frequencies of propellant atomization, evaporation, and combustion match acoustic resonance frequencies in the chamber components.

Analysis of acoustic amplification by combustion processes in liquid rocket combustion chambers is very difficult due to its very complex nature. In practice, a variety of approximations have been made to simplify the analysis. Many existing analytical models of combustion instability rely on linear stability theory and can generally predict whether an infinitesimal disturbance will grow or decay. There are, however, only a few nonlinear theories of combustion instability, and they are limited by severe assumptions. It is generally recognized that numerical integrations of unsteady Navier-Stokes equations coupled with chemical kinetics and diffusion processes will provide the ultimate solutions. As a first step toward achieving that goal, the Euler equations are employed to simulate the acoustic waves in combustors coupled with variable combustion rate. The state-of-the-art high resolution total-variation-diminishing (TVD) schemes are used to discretize the inviscid flux. These schemes have several favorable properties such as monotonicity preserving, low dissipation, and no problem-specific coefficients. They have achieved great success in modeling compressible flow with strong discontinuities such as shock waves.[1–3] To the authors' knowledge, it has not been fully assessed whether they can resolve the complex flow features in a combustion chamber environment. The current study sets out to address this problem. Four of the most popular TVD limiters are implemented to carry out the simulation. Their dissipation and dispersion errors are assessed by testing on several cases with exact solutions.

## Numerical Methodologies

The unsteady Euler equations in integral form can be written as

$$\int_V \frac{\partial}{\partial t} \, dV + \int_s F \, dS = 0 \tag{1}$$

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