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# High-repetition rate measurements of temperature and thermal dissipation in a non-premixed turbulent jet flame

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**Abstract**

High-repetition rate laser Rayleigh scattering is used to study the temperature fluctuations, power spectra, gradients, and thermal dissipation rate characteristics of a non-premixed turbulent jet flame at a Reynolds number of 15,200. The radial temperature gradient is measured by a two-point technique, whereas the axial gradient is measured from the temperature time-series combined with Taylor's hypothesis. The temperature power spectra along the jet centerline exhibit only a small inertial subrange, probably because of the low local Reynolds number ($Re_\delta \approx 2000$), although a larger inertial subrange is present in the spectra at off-centerline locations. Scaling the frequency by the estimated Batchelor frequency improves the collapse of the dissipation region of the spectra, but this collapse is not as good as is obtained in non-reacting jets. Probability density functions of the thermal dissipation are shown to deviate from lognormal in the low-dissipation portion of the distribution when only one component of the gradient is used. In contrast, nearly log-normal distributions are obtained along the centerline when both axial and radial components are included, even for locations where the axial gradient is not resolved. The thermal dissipation PDFs measured off the centerline deviate from log-normal owing to large-scale intermittency. At one-half the visible flame length, the radial profile of the mean thermal dissipation exhibits a peak off the centerline, whereas farther downstream the peak dissipation occurs on the centerline. The mean thermal dissipation on centerline is observed to increase linearly with downstream distance, reach a peak at the location of maximum mean centerline temperature, and then decrease for farther downstream locations. Many of these observed trends are not consistent with equivalent non-reacting turbulent jet measurements, and thus indicate the importance of understanding how heat release modifies the turbulence structure of jet flames.


*Keywords:* Turbulent flame; Scalar dissipation; Rayleigh scattering

## 1. Introduction

Detailed measurements of mean and fluctuating scalars, such as species mass fractions and temperature, have been critical to developing an improved understanding of the physics of turbulent non-premixed flames [1–4]. Of particular importance are the mixture fraction $\xi$ and its gradients, because in the flamelet theory the flame structure is fundamentally related to the value of $\xi$ at stoichiometric conditions and the rate of scalar dissipation, $\chi \equiv 2D\ (\nabla\xi \cdot \nabla\xi)$, where $D$ is the

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diffusivity. The scalar dissipation rate, which is a measure of the mixing rate, limits the reaction rate under mixing limited conditions, and affects the degree of non-equilibrium under finite chemistry conditions. Because of its importance to combustion, measurements of $\chi$ in turbulent non-premixed flames have received a lot of attention in recent years [5–7], but detailed statistical measurements of the type that exist for non-reacting flows are still relatively sparse.

It can be argued that temperature does not play as fundamental a role as mixture fraction in determining the flame characteristics, but its fluctuations and gradients do provide important information about the underlying mixture fraction structure. This can be seen by considering the thermal dissipation rate $\chi_T = 2\alpha(\nabla T \cdot \nabla T)$, where $T$ is the temperature and $\alpha$ is the thermal diffusivity, which is related to the rate of thermal mixing, or alternatively to the rate at which thermal inhomogeneities are removed by diffusion. Importantly, under the assumption of the state relationship $T = T(\xi)$ and unity Lewis number, the scalar and thermal dissipation rates are related as $\chi_T = \chi(\mathrm{d}T/\mathrm{d}\xi)^2$ [8]. As will be discussed in Section 4, in some regions of the flame, $\mathrm{d}T/\mathrm{d}\xi$ is approximately constant, and so the thermal dissipation rate is proportional to the scalar dissipation rate.

Thermal mixing is also important because it affects high-temperature chemical reaction processes and can be important in the development and validation of turbulent flame models [8]. For these reasons, fluctuating temperature and thermal dissipation rates have been measured in a number of studies by using, e.g., dual-thermocouple measurements [9,10], two-point laser Rayleigh measurements [11,12], and planar laser Rayleigh imaging [8]. An important issue with such measurements is that the requirement to obtain fully spatially and temporally resolved measurements of the finest scales of turbulence is very stringent and this makes dissipation measurements, in particular, challenging [13]. It is clear from a careful study of the literature that the Batchelor scale is rarely resolved, even in turbulent flame studies that explicitly seek to measure the dissipation rate.

The objective in this study was to make high-quality, high-repetition rate (10 kHz), two-point laser Rayleigh temperature measurements in a weakly co-flowing turbulent non-premixed jet flame at a Reynolds number of 15,200, with high signal-to-noise ratio ($\sim$50 in room air) and where the finest scales of turbulence are spatially and temporally resolved. These two-point temperature data were used to obtain temperature power spectra and detailed statistics of the thermal dissipation rate. The flame studied here is similar to the TNF simple jet flame (DLR_A), which is used as a benchmark flame for the TNF Workshop [14–17].

## 2. Experimental setup

The flow studied was a weakly co-flowing jet flame. The co-flow air was filtered to remove particles larger than 0.2 μm and then passed through a flow conditioning section. The co-flow velocity was 0.45 m/s. The fuel issued from a long tube with inside diameter $d = 7.75$ mm. The test section had a 0.75 m × 0.75 m cross-section. The whole jet flow facility was mounted on a traverse that was driven by stepper motors to provide positioning in the radial and axial directions. The fuel composition used in this study was 22.1% $CH_4$, 33.2% $H_2$, and 44.7% $N_2$ (by volume), which gives a stoichiometric mixture fraction of 0.167. The fuel gases were metered by pressure regulators and monitored by mass flowmeters to an accuracy of ±1.0 SLPM for $N_2$ and ±0.5 SLPM for $CH_4$ and $H_2$. The Rayleigh cross-section of this fuel has been shown to vary by ±3% across the whole flame [15]. The source Reynolds number was $Re_{d=U_0}d/v_0 = 15{,}200$ (where $v_0$ is the kinematic viscosity of the fuel and $U_0$ is the jet exit bulk velocity), and the measurements were taken at downstream locations from $x/d = 40$ to 80. Here, $x$ and $r$ are the axial and radial coordinates, respectively. The visible flame length was at about $x/d = 84$, and the stoichiometric flame length, estimated based on data in the TNF database, was at about $x/d = 60$.

The laser Rayleigh system is based on a diode-pumped Nd:YAG laser operated at 71 W average power at 532 nm and with a 10 kHz repetition rate. The laser beam was focused into the test section by using a 300 mm focal length lens. The beam diameter was measured to be about 0.3 mm. An external photodiode was used to correct for variations in the laser pulse energy on a shot-by-shot basis. Rayleigh scattered light was collected using custom-designed optics that consisted of a pair of 150 mm diameter plano-convex lenses, one 50.8 mm diameter meniscus lens and one 50.8 mm diameter double-convex lens. The lens system was designed with ZEMAX and produced an aberration-limited blur-spot of less than 34 μm. The working *f*# was 2.4, and the magnification was 0.685. Two-point measurements were made by imaging the scattered light onto a broadband hybrid cube beam splitter, which reflected and transmitted the split signal onto two different PMTs. Two 200 μm slits were placed in front of the PMTs to define the spatial resolution (i.e., length of the beam imaged). The slit width in the image plane corresponded to 300 μm in the object plane. These two slits were arranged such that the separation of probe volumes in the flow was 300 μm. The PMT and photodiode outputs were read by gated integrators operated with gate widths of 300 ns. The integrated signals were synchronously sampled by a 12-bit A/D converter at 10 kHz.