PASSIVE SCALAR MIXING OF A TURBULENT JET EMITTED INTO HOMOGENEOUS, ISOTROPIC TURBULENCE

Alejandro Pérez-Alvarado[1], Laurent Mydlarski[1] & Susan Gaskin[2]
[1]*Department of Mechanical Engineering, McGill University, Montréal, Canada*
[2]*Department of Civil Engineering and Applied Mechanics, McGill University, Montréal, Canada*

Abstract Although most jets, whether they be natural or industrial in origin, are emitted into a turbulent environment, almost all previous research on turbulent jets has dealt with jets emitted into quiescent or laminar background flows. The present work extends the work of Khorsandi, Gaskin and Mydlarski, *J. Fluid Mech.*, 2013 – who studied the effect of background turbulence on the velocity field of a turbulent jet emitted into turbulent surroundings – to the study of passive scalar mixing of a jet released into a turbulent flow. To this end, the experiments described herein use planar laser-induced fluorescence to study the mixing of a (high-Schmidt-number) passive scalar within a turbulent jet that is emitted into a quasi-homogeneous, isotropic, zero-mean-flow turbulent background. We examine herein statistics of the jet's scalar field, and compare them to those of a jet emitted into a quiescent background.

INTRODUCTION

Turbulent jets are ubiquitous in both natural and industrial settings, and have been extensively studied for the last 4-5 decades. Yet, the vast majority of studies of turbulent jets consider jets emitted into quiescent or laminar backgrounds (some exceptions being Refs. [1, 2, 3, 4, 5]). This is somewhat problematic with respect to the understanding and prediction of turbulent jets in "real" settings (natural or industrial), as most jets are, in fact, emitted into turbulent surroundings (*e.g.* emission of a pollutant from a smokestack into the atmospheric boundary layer, or injection of a fuel jet into a combustion chamber). Gaskin *et al.* [2] demonstrated that the effect of a turbulent background on the velocity and passive scalar fields of a plane jet in a shallow co-flow was to reduce the mixing and hence dilution of pollutants. The present work aims to investigate this result in the fundamental case of an axisymmetric jet emitted into an environment with no mean flow to elucidate the physical processes by examining the evolution of the passive scalar field in a turbulent background.

The present work builds that of Khorsandi, Gaskin and Mydlarski [5], who studied the effect of background turbulence on the hydrodynamic (*i.e.* velocity) field of a turbulent jet emitted into a turbulent environment. By way of flying-hot-film anemometry and acoustic Doppler velocimetry, they studied the evolution of the velocity fields of jets released into quasi-homogeneous, isotropic, zero-mean-flow turbulent backgrounds (of different intensities). Zero-mean-flow turbulence was chosen to eliminate the (additional) effect of mean flow advection, thus isolating the effect of the turbulence on the jet's evolution. The turbulent background was generated by means of a random jet array [6]. In addition to measuring faster decays of the mean centreline velocity, increased jet spreading rates, and increased levels of turbulence in the jet, Khorsandi *et al.* [5] also observed that the mass flow rate of a jet *decreased* in the presence of background turbulence – an interesting result confirming the findings of Gaskin *et al.* [2] indicating that the entrainment rate into a jet emitted into a turbulent background is reduced. For the current flow configuration this may imply reduced levels of mixing (and therefore reduced dilution of pollutants, for example) when jets are emitted into turbulent backgrounds once validated by concentration measurements. In this abstract, we present statistics of the concentration field for jets emitted into both quiescent and turbulent backgrounds, and discuss the observed differences.

EXPERIMENTAL APPARATUS AND FLOW CONDITIONS

The work was performed in the same experimental apparatus as Khorsandi *et al.* [5], with the addition of a planar laser-induced fluorescence system to allow measurements of the concentration (of disodium fluorescein, $Sc = 2 \times 10^3$) in the jet. The experiments were carried out in a $1.5 \times 2.4 \times 0.9$ m^3 section of a glass tank ($1.5 \times 6 \times 0.9$ m^3) containing water in the Environmental Hydraulics Laboratory in the Department of Civil Engineering and Applied Mechanics at McGill University. A random jet array [6] – consisting of 10 columns of 6 bilge pumps, randomly turned on and off, and attached to a vertical sheet of high density polyethylene (1×1.5 m) – was used to generate the quasi-homogeneous and isotropic, zero-mean-flow background turbulence. (See Khorsandi *et al.* [5] for more details.) The resulting background turbulence had a turbulent kinetic energy ($1/2\langle u_i u_i \rangle$) of 4.4 cm^2 s^{-2} (i.e. $u_{RMS} = 1.7$ cm s^{-1}), an integral length scale (ℓ) of 12 cm, and a turbulent Reynolds number (= $u_{RMS}\ell/\nu$) of 2000. The jet emanating into the turbulent background had a jet exit velocity (U_j) of 1.33 m s^{-1}, a jet exit diameter (D) of 8 mm, and a jet Reynolds number (= $U_j D/\nu$) of 10,600.

RESULTS

We begin by plotting in figure 1 the normalized radial mean concentration profile (C/C_o vs. r/x) for 4 downstream distances ($x/D =$ 20, 30, 40 and 50). Along the jet axis ($r = 0$), we observe the measured concentration to be *lower* for the jet emitted into a turbulent background than for one emitted into a quiescent environment. The decay rate of the normalized mean centreline concentration is thus more rapid for the jet emitted into a turbulent background. It follows a $x^{-1.3}$ power-law decay (inferred from a plot of $C(x = 0)/C_o$ vs. x/D – not shown) and is more rapid than the (expected) x^{-1} decay rate observed for the jet in a quiescent background. We furthermore note that it could be argued that the more rapid decay of the mean centreline concentration for a jet in a turbulent background contradicts the previously-mentioned conjecture that the mixing undergone by a jet emitted into a turbulent background might be reduced in a turbulent background. (Recall that this hypothesis was proposed by Gaskin *et al.* [2] and hypothesized by Khorsandi *et al.* [5] after observing that background turbulence served to reduce the entrainment into a jet and assuming this would lead to lower dilution rates.) This being said, the jet in a turbulent background indeed exhibits higher concentrations at off-axis (i.e $r/x > 0$) locations, which can be attributed to the increased width of a jet emitted into background turbulence. In either case, the question merits further study as the physics are not yet entirely clear.

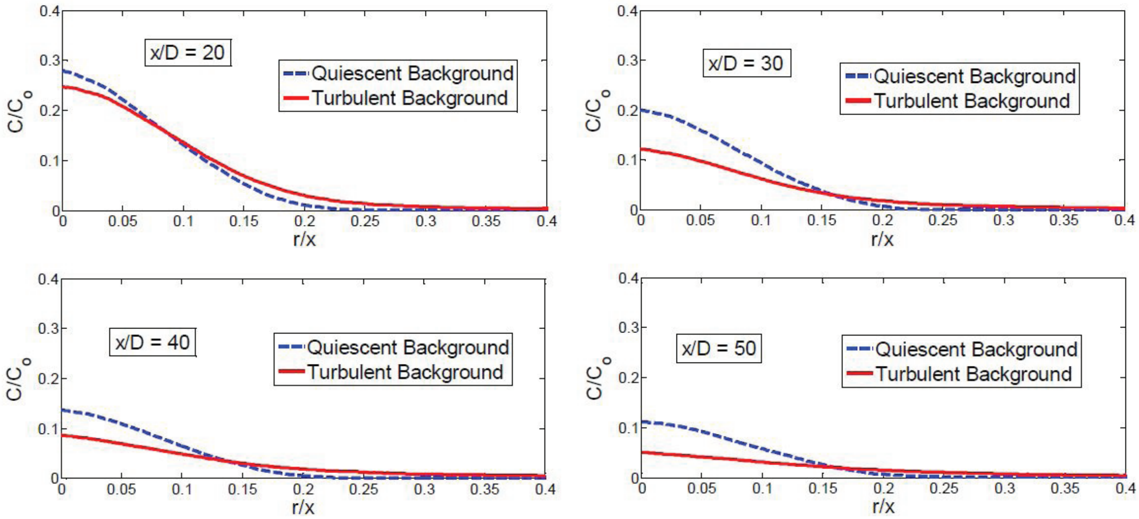

Figure 1. Radial (r) profiles of the mean concentration (C), normalized by the jet-exit concentration (C_o), at 4 downstream locations: $x/D = 20$, 30, 40 and 50.

To further examine the effect of background turbulence on the width of the jet, we plot the downstream evolution of the half-width of the jet's scalar field ($r_{1/2}$) as a function of downstream distance for releases in both quiescent and turbulent backgrounds. Near the jet exit (i.e. for $x/D < 20$), the momentum of the jet is high enough for the scalar field of the jet to not be substantially affected by the background turbulence. However, as x/D increases, the background turbulence serves to increase the jet half-width (as compared to a jet in a quiescent background), given that its velocity fluctuations become increasingly stronger relative to those of the jet itself.

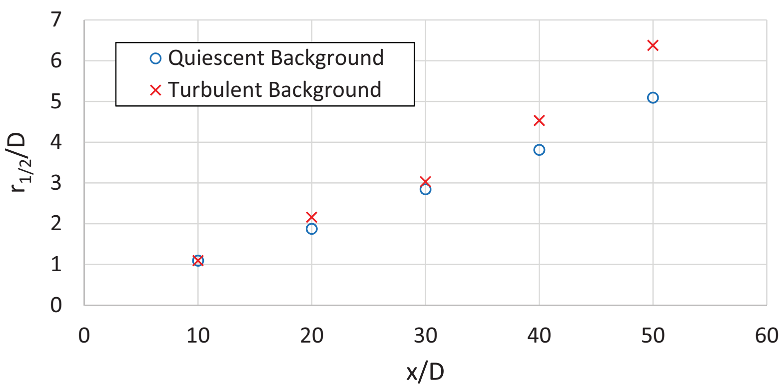

Figure 2. Downstream (x) evolution of the half-width ($r_{1/2}$) of the scalar field .

In the full paper, we will i) present additional results – including higher-order statistics (such as RMS concentration profiles) and probability density functions of the concentration, ii) investigate additional intensities of background turbulence, and iii) compare the effect of background turbulence on the jet's hydrodynamic and scalar fields.

References

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