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Study of the interference of plumes released from two near-ground point sources in an open channel

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ABSTRACT

The dispersion and mixing of passive scalars released from two near-ground point sources into an open-channel flow are studied using direct numerical simulation. A comparative study based on eight test cases has been conducted to investigate the effects of Reynolds number and source separation distance on the dispersion and interference of the two plumes. In order to determine the nonlinear relationship between the variance of concentration fluctuations of the total plume and those produced by each of the two plumes, the covariance of the two concentration fields is studied in both physical and spectral spaces. The results show that at the source height, the streamwise evolution of the cross correlation between the fluctuating components of the two concentration fields can be classified into four stages, which feature zero, destructive and constructive interferences and a complete mixing state. The characteristics of these four stages of plume mixing are further confirmed through an analysis of the pre-multiplied co-spectra and coherency spectra. From the coherency spectrum, it is observed that there exists a range of 'leading scales', which are several times larger than the Kolmogorov scale but are smaller than or comparable to the scale of the most energetic eddies of turbulence. At the leading scales, the mixing between the two interfering plumes is the fastest and the coherency spectrum associated with these scales can quickly approach its asymptotic value of unity.

1. Introduction

In engineering and environmental applications, one frequently encounters turbulent dispersion and mixing of passive scalars released from multiple concentrated (point or line) sources. For instance, in atmospheric pollution, hazardous materials are often released from multiple sources that are close to each other. Also, in nature, the precise detection of the exact locations of multiple food sources using the olfactory system is critical to the survival of many predatory and non-predatory animals. In most of these applications, the dispersion of gases and vapors in the air (Schmidt number ≈ 1) is of primary interest. Also, the sources are often located at ground level, where the flow is inhomogeneous and anisotropic. This further imposes challenges to the study of the temporal and spatial development and mutual interaction of passive scalar plumes, since most of the current theoretical models available for predicting turbulent dispersion and mixing of two or more scalars have been primarily limited to homogeneous and isotropic turbulent flows.

The dispersion and interference of plumes released from two or more point sources are determined by many factors including the source sizes, length scales of the plumes and turbulent eddies, and mean and fluctuating velocities. The relative length scales of the scalar and turbulent eddies influence significantly the plume dispersion patterns. For a single plume, if the size of the plume is smaller than that of the most energetic scale of turbulent motions, the plume meanders with the flow. However, if the plume size is larger than the most energetic scale of the flow motion, the plume mixing exhibits a Brownian diffusion pattern. For the development of two and more plumes, the mechanism becomes more complicated because of plume interference and involvement of additional length scales such as source separation distances. Another challenge involved in the study of a multi-source release problem is that although the governing equation for the passive scalar is linear, the interaction of higher-order statistics of two scalar fields is typically nonlinear. Although, the first-order statistics of the total scalar (i.e., mean concentration) are linearly superposable, the second- and higher-order statistics of the total scalar (e.g., variance of concentration fluctuations) are not.

Despite the importance of the subject, studies on the interaction of passive scalars emitted from multiple concentrated sources are

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Nomenclature

c	instantaneous concentration
C	mean concentration
$Co_{c'_A c'_B}$	co-spectrum of concentration fluctuations
d	source separation distance
$E_{c'c'}$	power spectrum of concentration fluctuations
$E_{w'w'}$	power spectrum of spanwise velocity fluctuations
f	frequency
f^*	non-dimensionalized frequency: $f\delta/u_\tau$
k	wavenumber
L	channel length
M	meandering ratio: σ_c^2/σ_r^2
N	number of grid nodes
p	pressure
r	local ratio of the upstream to downstream gradient in the concentration field
Re_τ	Reynolds number based on the wall friction velocity: $u_\tau\delta/\nu$
Sc	Schmidt number: ν/α
t	time
T	temporal interval: δ/u_τ
u	velocity component in the streamwise direction
u_i	velocity components: $i = 1, 2, 3$
u_τ	wall friction velocity
U	mean velocity in the streamwise direction
v	velocity component in the wall–normal direction
w	velocity component in the spanwise direction
x_i	coordinates: $i = 1, 2, 3$
z_c	instantaneous plume centroid

Greek symbols

α	molecular diffusivity of the scalar
δ	channel height
Δ	grid size
λ	size of turbulent eddies
ν	kinematic viscosity
ρ_{cc}	cross correlation coefficient between concentration fluctuations
ρ_{cs}	coherency spectrum
ϱ	density
σ_c	instantaneous plume centroid dispersion
σ_r	relative plume dispersion
σ_z	mean plume dispersion
Σ_r	relative plume half width
Σ_z	mean plume half width
ψ	limiter function

Subscripts

$(\cdot)_A$	value for the plume released from source A
$(\cdot)_B$	value for the plume released from source B
$(\cdot)_m$	maximum value
$(\cdot)_{mid}$	value at the midpoint in the spanwise direction between the two plumes
$(\cdot)_r$	value in the relative frame
$(\cdot)_{rms}$	root-mean-squared quantity
$(\cdot)_s$	value at the source
$(\cdot)_T$	value for the total plume
$(\cdot)_x$, $(\cdot)_y$, $(\cdot)_z$	streamwise, wall–normal, and spanwise components, respectively
$\overline{(\cdot)}$	time-averaged quantity
$(\cdot)^+$	wall coordinates
$(\cdot)'$	fluctuating component

Abbreviations

DNS	direct numerical simulation
MPI	message passing interface
TVD	total variation diminishing
SMART	sharp and monotonic algorithm for realistic transport

still rather limited in the literature. Based on wind-tunnel measurements, Warhaft (1984) investigated the interference of passive thermal fields produced by two line sources in decaying grid turbulence. He observed that the interference between the two thermal plumes may alter the total temperature variance level, and this effect varies with the separation distance between the two line sources, source position from the grid, and downstream location where the measurements were taken. Stapountzis (1988) conducted a series of wind-tunnel experiments to investigate the mixing of two passive thermal plumes generated from two line sources separated in either the spanwise or streamwise directions. He found that there was a strong negative correlation between the temperature fluctuations within the meandering regime of plume development released from two transversely separated line sources, and that the correlation coefficient became positively valued when the two line sources were aligned in the streamwise direction. Tong and Warhaft (1995) investigated the dispersion and mixing of passive scalars produced by two heated fine rings placed axisymmetrically in a turbulent jet. Their results on the coherency spectrum of concentration fluctuations of the two plumes showed that the small scales lag behind the large scales in the mixing of two plumes. Davis et al. (2000) studied the interaction of plumes released from two point sources into the atmospheric boundary layer. Their measurement results on two laterally separated sources showed that the correlation between the concentration fluctuations of the two plumes change from negative to positive as the downwind distance increases for a fixed source separation distance, or as the source separation distance decreases for a fixed downwind location.

Vrieling and Nieuwstadt (2003) performed direct numerical simulation (DNS) to study the interference of two nearby line sources in a plane-channel flow. They placed their line sources at the center of the channel to emulate a concentration release in homogeneous turbulence, and observed that the covariance between the two plumes depends on the spacing between the sources and the downstream distance from the sources. They also obtained an analytical expression for the combined variance of the total concentration fluctuation based on the well-known meandering plume model of Gifford (1959). With their analytical model, Vrieling and Nieuwstadt (2003) were able to compute statistics related to the interference of concentration plumes under practical atmospheric dispersion conditions where the meandering effect is strong. However, at far downstream locations where the effect of plume meandering reduces significantly, their model failed to predict the numerical results. Yee et al. (2003) used a meandering plume model incorporating internal fluctuations to provide explicit analytical expressions for various higher-order joint concentration statistics for plume arising from a two point source release in homogeneous isotropic turbulence. The model prediction of Yee et al. (2003) on the second-order correlation function (cross correlation) between the concentration fluctuations were in good agreement with some experimental data for a two point source release in grid turbulence acquired in a water-channel simulation. Costa-Patry and Mydlarski (2008) conducted a wind-tunnel