Mixing and dispersion in unsteady plumes

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We study longitudinal mixing in a statistically unsteady turbulent plume at $Re = 2400$ using direct numerical simulation (DNS) by instantaneously increasing the source buoyancy flux by a factor of two. The focus is on the behaviour of the plume's integral quantities, including the volume flux, momentum flux and buoyancy flux, in the vicinity of the resulting front. The front separates regions of relatively high and low buoyancy flux and propagates in the longitudinal direction with a velocity that is proportional to the local characteristic velocity of the plume. We present results from both steady and unsteady plumes and discuss the role of longitudinal turbulence transport and shear-flow dispersion in determining the propagation velocity of the front and its mixing properties in the unsteady case. We employ a momentum–energy framework [1], in place of the classical mass–momentum formulation [2], generalising a decomposition of the entrainment coefficient [3] to unsteady problems.

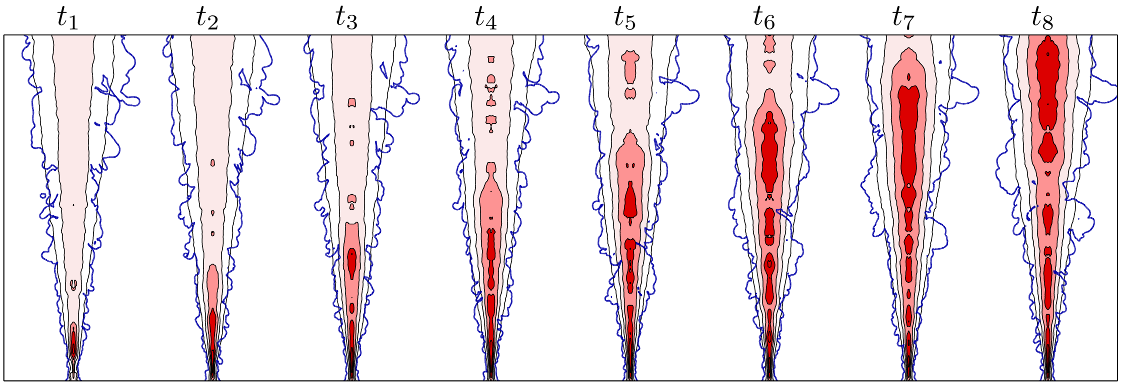

Fig. 1: Isoregions of the ensemble and azimuthally-averaged buoyancy (red) and threshold of the instantaneous enstrophy (blue) in an unsteady turbulent plume at times $t_1 \dots t_8$. The quantities displayed in the figure are non-dimensionalised using the local characteristic scales of a steady plume.

In an unsteady context the momentum–energy framework exposes features of plumes that are hidden in the steady state, revealing that properties such as entrainment and the radius of the plume depend on the dimensionless energy flux, buoyancy flux, and turbulence production independently. We will discuss the way in which these dimensionless quantities define the hyperbolic nature of the governing integral equations and the behaviour of the flux balance parameter $\Gamma(z, t)$ in the vicinity of the front. In general, for a given density stratification in the ambient, the dimensionless parameters also determine the way in which a plume responds to perturbations in the source buoyancy flux.

Utilising a dispersion closure developed for jets [4], we propose a model for unsteady plumes that incorporates shear-flow dispersion, and therefore accounts for the fact that statistical unsteadiness in plumes forces a departure from the self-similarity that one finds in steady plumes. The model shows a good agreement with the DNS results, capturing both the position and longitudinal extent of the front and characteristic features of the plume's leading-order integral quantities. Motivation for this work comes from the recent discovery that several existing unsteady plume models are ill-posed [5] in the absence of an appropriate description of longitudinal mixing. The dispersion closure we present has the desirable feature of being valid for both unsteady plumes and unsteady jets, not modifying the classical solutions to the steady-state plume equations and can be used to model the longitudinal mixing of both the mean kinetic energy and buoyancy.

References

[1] Priestley CHB & Ball FK. *Q.J.R. Meteorol. Soc.*, **81**:144-157, 1955.
[2] Morton BR, Taylor GI & Turner JS. *Proc. Roy. Soc.*, **234**:1-23, 1956.
[3] Kaminski E, Tait S & Carazzo G. *J. Fluid Mech.*, **526**:361-376, 2005.
[4] Craske J & van Reeuwijk M. *J. Fluid Mech.*, **763**:538-566, 2015.
[5] Scase MM & Hewitt RE. *J. Fluid Mech.*, **697**:455-480, 2012.

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