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M.S.Chandrasekhara, and B.R.Ramaprian, Intermittency and Length Scale Distributions in Plane Turbulent Plumes, Trans. ASME Journal of Fluids Engineering, Vol. 112, No. 3, pp. 367-369, Sep. 1990.
http://hdl.handle.net/10945/50061

Journal of Fluids Engineering
# Technical Briefs

## Intermittency and Length Scale Distributions in a Plane Turbulent Plume

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*Previous studies have shown that normalized Reynolds shear stress and turbulent heat fluxes in asymptotic plane turbulent plumes are significantly higher than in asymptotic plane turbulent jets. This paper describes an attempt to relate this increase to the length scales in the flow. Hot/cold interface intermittency and integral-length-scale distributions were measured in both these flows. The interface-intermittency distributions were found to be bell-shaped in the plume in contrast to a nearly top-hat shape in a jet, thus providing confirmation of the role of buoyancy in generating larger scales in plumes. These larger scales cause the integral length of turbulence in the plume to increase by nearly 15 percent relative to the non-buoyant jet.*

### Nomenclature

$b_u$ = velocity half width
$b_t$ = temperature half width
$D$ = nozzle width at exit
$f_c$ = hot/cold interface crossing frequency
$g$ = acceleration due to gravity
$l_u, l_v$ = integral length scales for $u$ and $v$ velocity fluctuations
$R_j$ = exit Richardson number = $\left(\frac{-\Delta\rho_j}{\rho_j}\right)\frac{gD}{U_j^2}$
$R_{uu}, R_{vv}$ = correlation functions for $u$ and $v$ fluctuations
$\overline{T}$ = local mean temperature excess
$T_a$ = ambient temperature
$\overline{t^2}$ = mean square temperature fluctuations
$t_\phi$ = time scale
$U_j$ = jet exit velocity
$U_m$ = centerline velocity
$\overline{U}, \overline{V}$ = mean velocities in the $x$ and $y$ directions
$\overline{u^2}, \overline{v^2}$ = mean square velocity fluctuations
$x, y$ = coordinates along and perpendicular to flow axis
$\Delta T_j$ = exit temperature excess
$\eta$ = $\frac{y}{b_u}$
$\rho_j$ = density at nozzle exit
$\Omega$ = hot/cold interface intermittency

### 1 Introduction

Early studies by Rouse et al. [1] established the basic growth and decay laws of plane turbulent jets and plumes. In a plume flow, the driving force is buoyancy, i.e., a plume orginates from a source of buoyancy. In a plane plume, the buoyancy and momentum forces are comparable. On the other hand, a jet flow is due to a source of momentum. Figure 1 describes the characteristics of a jet and plume. Kotsovinos [2] characterized the behavior of the velocity and temperature fluctuations as well as the turbulent/nonturbulent interface in a plume flow. More recently, Ramaprian and Chandrasekhara [3, 4, 5] measured both the mean and turbulence properties in asymptotic plane plumes. These studies have shown that, when properly scaled by using the centerline velocity $U_m$ and the half widths $b_u$ or $b_t$ (of the velocity or temperature distributions, respectively), the normalized turbulent stresses and heat fluxes are significantly higher in plumes. In particular, the normalized Reynolds shear stress has been found to be about 50 percent higher in plumes than in jets. This is seen from Fig. 2 taken from [5]. Such large increases imply corresponding increases in the eddy momentum and thermal diffusivities. This increase has been attributed to the production of larger scales in the flow by gravitational instability induced by buoyancy (Kotsovinos [2]). This note reports some quantitative results of comparative measurements of the intermittency and integral length scales in plumes and jets. These results not only confirm that buoyancy increases the length scales in the flow, but also would directly be useful in modelling such flows.

### 2 Experimental Procedure

*2.1 Description.* Plane turbulent jets and plumes were produced by injecting hot water vertically upward from a 250 mm span × 5 mm width ($D$) nozzle into cold water contained in a hydraulic flume. The details of the experimental set up and the individual experimental conditions can be found in [3]. The experiments of relevance to this paper are identified as MSC2, and MSC3. Flow MSC2 is a heated (but, slightly bouyant) vertical plane jet with an exit Richardson number of 0.0008. Flow MSC3 is a positively buoyant, plane plume flow with an exit Richardson number of 0.05, and reaches asymptotic state by $x/D$ = 30, where $x$ is the distance downstream from the plume exit. In both the cases, detailed experiments were carried out at streamwise stations corresponding to $x/D$ = 30 and 50. Table 1 lists the exit conditions namely, the exit velocity $U_j$, exit temperature $T_j$, and ambient temperature $T_a$ for the two flows. The mean and turbulent flow properties of these flows have been fully documented in [4, 5].

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Contributed by the Fluids Engineering Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received by the Fluids Engineering Division June 6, 1989.

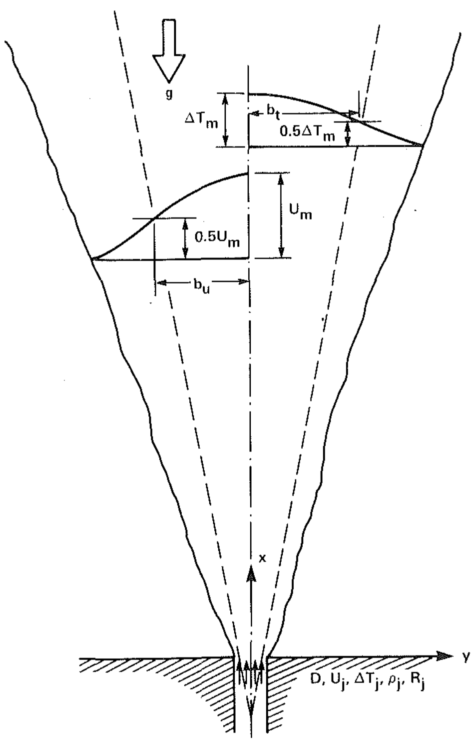


**Fig. 1 Schematic and nomenclature of a plane turbulent jet and plume**

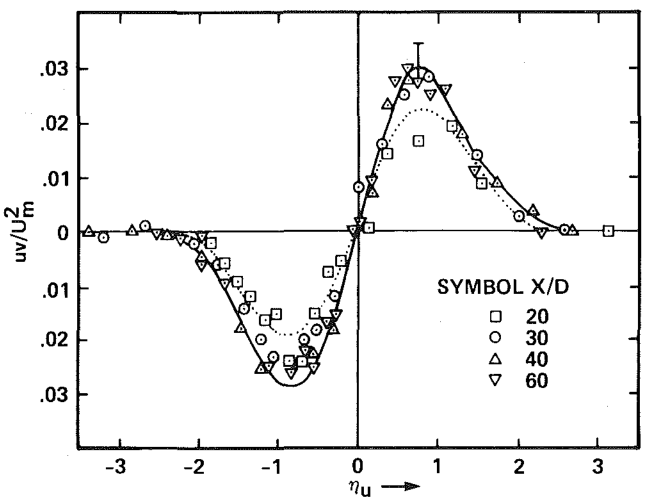


**Fig. 2 Reynolds shear stress distribution in plumes. Plume MSC3: x, x/D = 20, o, x/D = 30, Δ, x/D = 40, ∇, x/D = 60; ......, jet MSC2 (from [5]).**

Mean velocities ($\overline{U}$, $\overline{V}$) and turbulent stresses ($\overline{u^2}$, $\overline{v^2}$) were measured using two-component, frequency-shifted laser Doppler anemometry. The optics were set up in the forward-scatter mode and frequency trackers were used for signal processing. Temperature ($\overline{T}$) and its fluctuations ($\overline{t^2}$) were measured using cold-wire resistance thermometry. The data were low-pass filtered at 50 Hz, digitized at 100 Hz and acquired with a HP-1000 mini-computer. The sampling frequency of 100 Hz was selected after ascertaining that the spectral bandwidth of turbulence in the plumes was within 0–50 Hz. A total of 61440 samples per channel (of each $U$, $V$, and $T$) were collected. These data were used to compute the hot/cold interface intermittency, turbulent spectra, autocorrelations and length scales.

The integral scales were obtained from the autocorrelation functions $R_{uu}$ and $R_{vv}$ of $\overline{u^2}$ and $\overline{v^2}$, respectively. For this purpose, first the spectra of the turbulent velocity fluctuations $\overline{u^2}$ and $\overline{v^2}$ were estimated using the discrete fast Fourier transform technique. A total of 60 spectra, each computed over 1024 samples were used to obtain the mean spectrum in each case. Next, the autocorrelation functions were obtained by computing the inverse Fourier transform of the mean spectra. The integral time scale $t_\phi$ ($\phi = u$ or $v$) of turbulence was then obtained from the definition:

$$t_\phi = \int_0^\infty R_{\phi\phi}(\tau)d\tau. \qquad (1)$$

Finally, the integral length scale $l_\phi$ was obtained using the Taylor approximation: $l_\phi = -\overline{U}t_\phi$.

**Table 1 Experimental conditions**

| Flow designation | $U_j$ cm/s | $\Delta T_j$ °C | $T_a$ °C | $R_j$ |
|---|---|---|---|---|
| MSC2 | 30 | 3.29 | 23.0 | 0.0008 |
| MSC3 | 10 | 23.2 | 24.2 | 0.05 |

*2.2 Determination of Intermittency.* Since the experiments involved heated water being discharged into a cold ambient, one could use the instantaneous local temperature as a tracer for identifying the presence of the jet/plume fluid. In this so-called "heat tagging" technique, detection of the hot fluid anywhere indicates the presence of the jet/plume fluid there. Likewise, detection of the cold fluid implies the penetration of the ambient fluid into that region. This method of determining the hot/cold interface intermittency is very attractive because temperature can easily and reliably be measured. It has been used, in the past, by several researchers (see for e.g., Weir et al. [6]).

The digitized instantaneous velocity and temperature data recorded on disk were used for the estimation of the hot-cold intermittency. Following the usual procedure, a threshold level was selected to distinguish the "hot" fluid from the "cold" fluid. When the temperature level was higher than that of the threshold, the corresponding samples were accepted as "hot" samples. The rest were treated as "cold" samples. The intermittency Ω, was defined as the ratio of the number of hot samples to the total number counted. It is to be noted that Ω is a measure of the intermittency associated with the crossing of the probe volume by the hot/cold interface. It is not necessarily a measure of the turbulent/non-turbulent intermittency. A procedure, well established from earlier studies (LaRue, [7]), was followed in the selection of the threshold level, record length, sample size etc.

In addition to intermittency, the frequency with which the hot/cold interface crosses the probe volume was also determined. The crossing frequency $f_c$ is defined as the number of cross-overs per unit time in a given length of sample. No distinction was made between hot-cold and cold-hot crossings. The crossing frequency at each point was estimated at the same threshold level as that used for the estimation of Ω.

## 3 Results and Discussion

*3.1 Intermittency Studies.* The distribution of the hot/cold interfacial intermittency and the crossing frequency for flows MSC2 and MSC3 are shown in Figs. 3(*a*) and 3(*b*). In the jet, the intermittency is uniformly equal to 1 in the central part and drops sharply beyond $\eta = y/b_u \approx 1.0$. The distributions at $x/D = 30$ and 50 are seen to be fairly self-similar and resemble the distributions of turbulent/non-turbulent intermittency measured by Bradbury [8] and Gutmark and Wygnanski [9]. The distributions of the crossing frequency $f_c$, exhibit some asymmetry, but the maximum crossing frequency occurs at $\Omega \approx 0.5$, as expected. The frequencies encountered here are approximately 0 to 2.5 Hz which correspond to a nondimensional wave number range of $0 \le 2\pi f_c b_u/\overline{U} \le 3.0$.

In the plume, the intermittency at the centerline is $\approx 0.92 - 0.95$ at $x/D = 30$, instead of the normally expected value

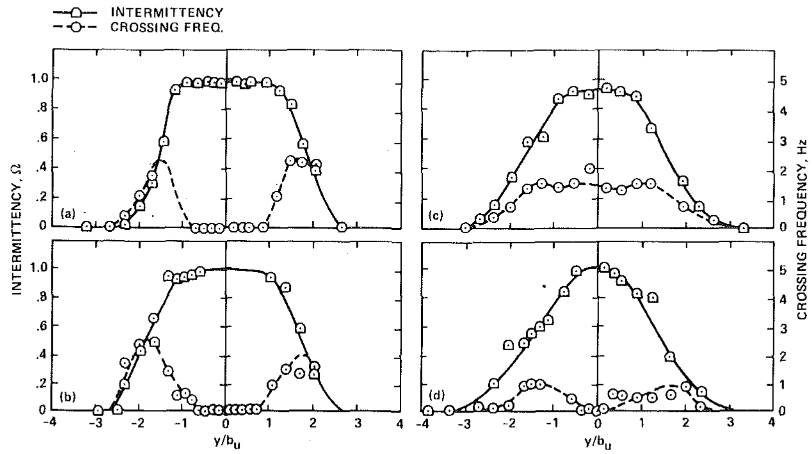


**Fig. 3 Intermittency and crossing frequency distributions. (*a*,*b*) Nonbuoyant jet MSC2; (*c*,*d*) Plume MSC3. Uncertainties: $y/b_u$: ±0.06; Ω: ±.05; crossing frequency: ±0.25 Hz.**

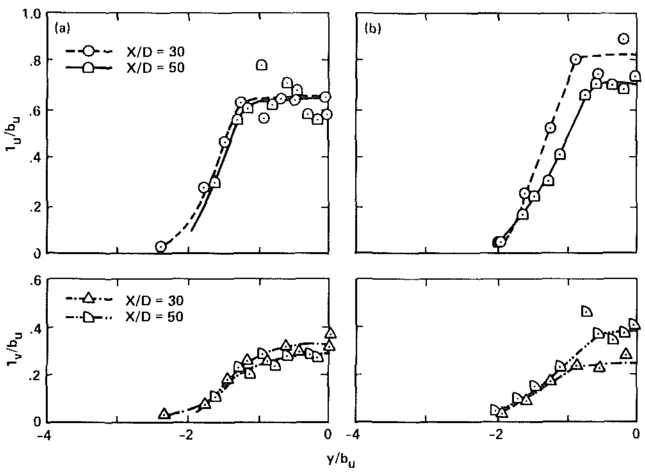


**Fig. 4 Distributions of length scales across the flow. (*a*) Nonbuoyant jet MSC2; (*b*) Plume MSC3. Uncertainties: $y/b_u$: ±0.06; $l/b_u$: ±0.06.**

of 1. This interesting result indicates the presence of cold fluid for about 5 to 8 percent of the time, in the core of the plume. It thus suggests that eddies larger than the width of the plume entrain the outer cold fluid at this station. The intermittency distribution evolves in the streamwise direction, and Ω attains a value of unity at the centerline by $x/D = 50$ (Fig. 3(*b*)). The more significant result, however, is the bell-shaped intermittency distribution in the asymptotic plume in contrast to a flat-topped distribution characteristic of nonbuoyant jets. The maximum crossing frequency in the plume at $x/D = 50$ is about 1 Hz which corresponds to a nondimensional wave number of about 1.3, a value significantly lower than the value of about 3 in the nonbuoyant jet.

The bell-shaped intermittency distribution indicates intermittent mixing in a large part of the interior of the plume, i.e., there is a significant amount of direct transport of ambient fluid by large eddies even in regions of maximum shear stress in the plume (around $\eta = 0.7$). In the case of the jet, the intermittency in this region is almost unity, indicating that large eddies do not penetrate this deep into the jet. The only manner in which the ambient fluid eventually mixes with fluid in the interior of the jet is via smaller scale interaction and transport. The intermittency studies, thus clearly indicate that the large eddies in the plume are larger than in a jet and are responsible for significant transport even near the core of the plume.

*3.2 Length Scale Distributions.* The presence of the relatively larger eddies in the plumes was also confirmed by the data on the integral length scales of turbulence in plumes and jets. The distributions across one half of the flow are presented in Fig. 4(*a*) and 4(*b*) for the nonbuoyant jet MSC2 and plume MSC3. Flow MSC2 has constant length scales $l_u$ and $l_v$ over the range $\eta = 0$ to 1. The distributions of these scales do not change appreciably from $x/D = 30$ to $x/D = 50$ in the jet, indicating a fairly well developed structure of the flow. In the plume MSC3, however, the length scales (especially $l_v$) increase as the plume evolves from $x/D = 30$ to 50. It can be seen that, on the average, both the length scales $l_u$ and $l_v$ are eventually increased by buoyancy by about 10 to 15 percent relative to the nonbuoyant jet.

## 4 Conclusions

The present study confirms that buoyancy augments the large scales of turbulent motions. These motions, which are of the order of the width of the plume, are responsible for causing the mixing between the plume and the ambient to be intermittent even in the region of maximum shear stress. They also cause the integral scales of turbulence in the plume to be about 10–15 percent higher than those in a nonbuoyant jet.

## Acknowledgment

The authors gratefully acknowledge the support received from the U.S. National Science Foundation for performing this research.

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