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Dispersion from elevated line source in a turbulent boundary layer

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NOMENCLATURE

d	source wire diameter
$\theta(x, y)$, $\theta_{max}(x)$, $\theta_w(x)$	mean temperature, peak value and wall value respectively
θ'	temperature fluctuation
U	mean streamwise velocity
v'	velocity fluctuation component perpendicular to the wall
Δx	streamwise distance from the source wire
y	distance from the wall
δ	99% boundary-layer thickness
T_L	temporal Lagrangian integral scale
Q	line source strength
l_L	vertical length scale, $\overline{(v'^2)}^{1/2} \cdot T_L$
L_L	streamwise length scale, UT_L
θ_A	temperature scale, $Q/\rho C_P U l_L$
$\bar{Y}$	centroid
$\overline{(Y-\bar{Y})^2}$	variance.

Subscripts

L	Lagrangian
s	source.

1. INTRODUCTION

RECENT papers have brought a large amount of experimental results on dispersion of passive scalar from line source or point source located in a turbulent boundary layer (see for example Shlien and Corrsin [1], Paranthoen and Trinite [2], Belorgey and Nguyen [3], Fackrell and Robins [4] and Raupach and Legg [5]). Several of these studies are both concerned with ground level and elevated sources. Due to the existence of many heat and mass transfer problems in turbulent flows close to solid boundaries the dispersion of a passive contaminant in a turbulent boundary layer is then important both from a fundamental and practical point of view.

However although detailed experimental results of both fluctuating velocity and scalar field are now available it turns out that analysis of influence of the source height on the longitudinal evolution of characteristics of scalar field is not well explained so far.

The authors had to answer this challenging question in order to compare results on dispersion of heat from elevated line source located in boundary layer with dissimilar thickness ($\delta_s = 8.8$ mm and 98 mm, δ_s being the boundary-layer thickness at the source location).

In fact, as shown by Poreh and Cermak [6] for the case of ground level source, in the 'intermediate' zone where the diffusing plume is submerged in the boundary layer, the mean-concentration profiles can be renormalized using the peak value θ_{max} and $y_{0.5}$ the distance for which $\theta/\theta_{max} = 0.5$.

However when these scales are used for the case of elevated source the longitudinal evolution of θ_{max} and $y_{0.5}$ is found to be very dependent on the source distance from the wall, Shlien and Corrsin [1], Paranthoen [7]. In the present paper it is shown that the data can be collapsed onto a single curve using the integral Lagrangian scale L_L for rescaling the streamwise distance from the source wire.

2. ANALYSIS

As shown by Shlien and Corrsin [1] when $\overline{(Y-\bar{Y})^2}$ (the variance of the mean temperature field $\theta(x, y)$ at a distance Δx from the source wire) is plotted as a function of Δx, linear regions can be observed. Although $\overline{(Y-\bar{Y})^2}$ is actually not a Lagrangian characteristic as discussed by Chatwin [8], it seems interesting, by analogy with the homogeneous situation studied by Taylor [9], to determine a Lagrangian integral scale $T_L(y_s)$ from

$$T_L(\bar{Y}) = \frac{U(\bar{Y})}{\overline{v_L'^2}} \frac{1}{2} \frac{d\overline{(Y-\bar{Y})^2}}{dx}. \qquad (1)$$

Assuming $\overline{v_L'^2} = \overline{v'^2}$ the experimental determination of $T_L(y_s)$ has been made by Paranthoen [7] and Dupont [13]. It is worth noting that for sake of simplicity, $U(y_s)$ and $\overline{v'^2}(y_s)$ have been used in relation (1).

From the results shown in Fig. 1 it appears that for the case of the turbulent boundary layer $T_L(y_s)$ can be reasonably approximated by the following relation

$$\frac{U(y_s)T_L(y_s)}{\delta_s} = 7.5\left(\frac{y_s}{\delta_s}\right)^{1.5} \qquad (2)$$

which seems valid for $0.05 < y_s/\delta_s < 0.6$. For values of y_s/δ_s smaller than 0.05 the use of Taylor hypothesis in relation (1) seems doubtful.

So to present results in dimensionless form we use two length scales L_L and l_L in order to characterize the scalar field in streamwise and normal directions respectively as follows

$$L_L = U(y_s)T_L(y_s) \qquad (3)$$

$$l_L = [\overline{v'^2}(y_s)]^{1/2} T_L(y_s). \qquad (4)$$

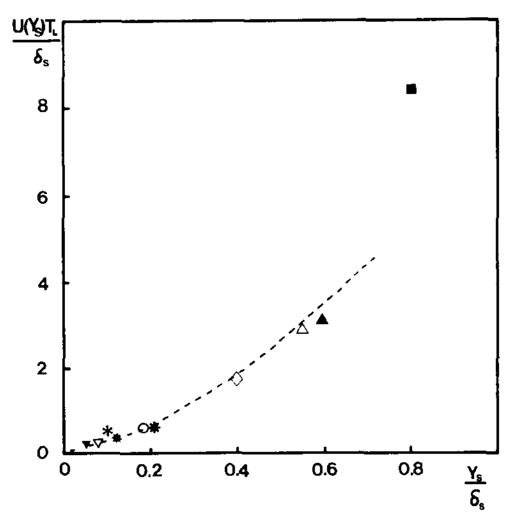

FIG. 1. Integral temporal Lagrangian scale; symbols as in Table 1.

Table 1. Main characteristics of the boundary layer

Ref.	δ_s (cm)	U (cm s^{-1})	$\frac{y_s}{\delta_s}$	$\frac{U(y_s)T_L(y_s)}{\delta_s}$	Figure symbols
Shlien and Corrsin [1]	5.15	1270	0.24	0.86	●
			0.62	3.65	★
Paranthoen [7]	0.88	2850	0.10	0.58	*
			0.18	0.52	○
			0.53	2.93	△
			0.8	8.43	■
Raupach and Legg [5]	54	1100	0.11	0.27	◆
Dupont [13]	9.8	690	0.05	0.24	▼
			0.075	0.25	▽
			0.12	0.35	✱
			0.2	0.6	✱
			0.4	1.72	◇
			0.6	3	▲

Furthermore the mean velocity at the source position $U(y_s)$ is used as a velocity scale and a temperature scale θ_A is defined by

$$\theta_A = \frac{Q}{\rho C_P U(y_s) l_L} \quad (5)$$

where Q is the line source strength, ρ and C_P are the air density and specific heat of air at constant pressure respectively.

The choice of l_L as a length scale in relation (5) is consistent with heat conservation in the initial stage of the diffusion process.

3. COMPARISON BETWEEN EXPERIMENTAL RESULTS

By using the scales defined above results issued from several dispersion experiments have been replotted. For the selected experiments Table 1 summarizes the main characteristics of the boundary layer at the source location as well as the source heights. This paper deals only with source heights such that $0.05 < y_s/\delta_s < 0.8$.

3.1. *Mean temperature profiles*

Mean temperature profiles measured downstream at an elevated line source can be characterized by the temperature peak θ_{max}, the wall temperature θ_w and the variance $\overline{(Y-\bar{Y})^2}$ of the mean temperature.

The temperature peak θ_{max} and the standard deviation $\{\overline{(Y-\bar{Y})^2}\}^{1/2}$ normalized with θ_A and l_L, respectively are plotted in Fig. 2 as a function of $\Delta x/UT_L$.

In the same way longitudinal evolution of the wall temperature θ_w normalized with θ_A is presented in Fig. 3. The data gather approximately onto a single curve regardless the source distance from the wall. It appears that the nondimensional ground level temperature θ_w/θ_A is found to be maximum at $\Delta x/UT_L \sim 8$–10 where $(\theta_w)_{max}$ is about 0.1–0.08 θ_A.

Power laws can be fitted to θ_{max}/θ_A data. When $\Delta x/UT_L < 0.5$, a -1 power fall-off is observed while when $\Delta x/UT_L > 5$ the power fall-off is about -0.5. The good agreement obtained for the streamwise evolution of characteristics of the mean temperature profiles has suggested to extend the test to the standard deviation of temperature fluctuations $(\overline{\theta'^2})^{1/2}$.

3.2. *Fluctuating temperature profiles*

Profiles of the standard deviation of θ' can be characterized by the peak value $(\overline{\theta'^2})^{1/2}_{max}$. Relative intensity $(\overline{\theta'^2})^{1/2}_{max}/\theta_{max}$ for the case of elevated line sources are plotted in Fig. 4 as a function of $\Delta x/UT_L$. It is worth noting that experimental

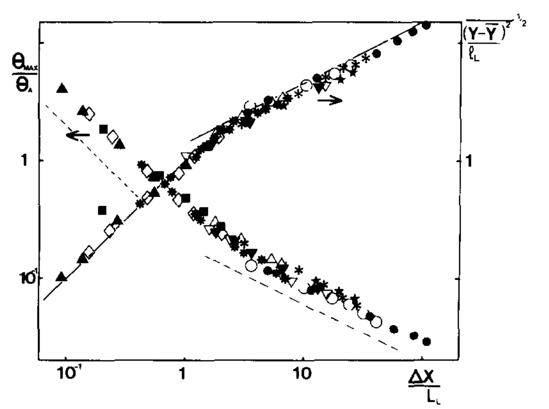

FIG. 2. Streamwise evolution of peak temperature and standard deviation $\{\overline{(Y-\bar{Y})^2}\}^{1/2}$; symbols as in Table 1.

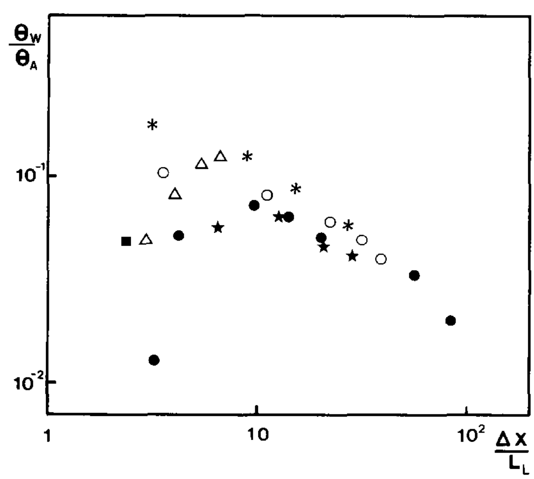

FIG. 3. Streamwise evolution of wall temperature: symbols as in Table 1.

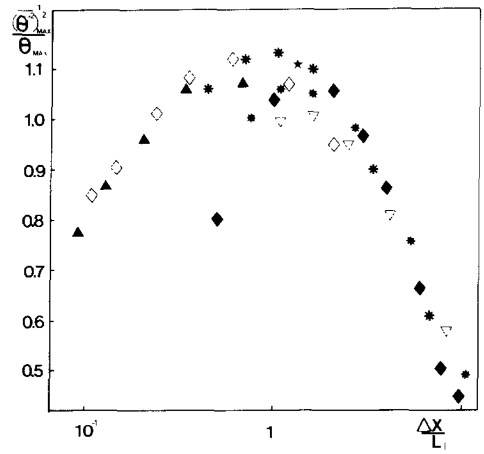

FIG. 4. Streamwise evolution of relative intensity of temperature fluctuations; symbols as in Table 1.

results issued from various experiments can be compared more easily in this dimensionless form. The differences observed between experimental results corresponding to similar relative source heights could be due to two independent phenomena which both lead to an attenuation of the standard deviation of θ'. The first one is related to the effect of source size on temperature fluctuation level as pointed out by Shlien [10], Durbin [11], Chatwin and Sullivan [12] and Fackrell and Robins [4]. The second one is linked to the imperfect response of the cold wire (sensor used to measure temperature fluctuations) due to thermal prong-wire interaction. For this reason measurements performed by Dupont [13] have been carefully corrected using the method proposed by Lecordier *et al.* [14].

It is worth noting that the evolution of $\overline{(\theta'^2)}^{1/2}_{max}/\theta_{max}$ in the first part of the diffusion process ($\Delta x/UT_L < 1$) shows that the 'meandering' is the major source of temperature fluctuations as mentioned by Fackrell and Robins [4] and Dupont [13].

4. CONCLUSION

The aim of this note has been to show that dispersion measurements from elevated line source ($0.05 < y_s/\delta_s < 0.8$) located in turbulent boundary layer can be compared in a better way using a rescaling scheme based on the temporal integral Lagrangian scale. This scheme has been used to compare the streamwise evolution of characteristics of mean temperature and θ' standard deviation profiles obtained in dissimilar boundary layers and could be extended to present detailed temperature statistics (higher moments, intermittency).

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