BUOYANT TURBULENT JETS AND FLAMES:
I. ADIABATIC WALL PLUMES

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Notice:

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Abstract

An investigation of the structure and mixing properties of buoyant turbulent plumes is described, motivated by the need to resolve effects of buoyancy/turbulence interactions and to provide data required to benchmark models of buoyant turbulent flows for fire environments. Flows considered in this part of the report include plane adiabatic wall plumes; a second part of the report will consider starting nonbuoyant and buoyant turbulent jets and plumes. Measurements included laser-induced fluorescence (LIF) to find mixture fraction statistics and laser velocimetry (LV) to find velocity statistics, emphasizing conditions far from the source where effects of source disturbances and momentum have been lost. The results show that earlier measurements in the literature were not carried out far enough from the source to provide self-preserving properties and that actual self-preserving adiabatic wall plumes are narrower than previously thought. Adiabatic wall plumes were also found to mix much more slowly than free line plumes because the presence of the wall inhibits access on one side of the flow and the development of large turbulent eddies that dominate the turbulent mixing processes in these flows. This reduced rate of mixing of turbulent wall plumes is a concern in fires because it extends the length of the flame-containing region and reduces the rates of dilution of the flow that is needed to reduce temperatures and toxic gas concentrations in fire plumes.

Acknowledgments

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Nomenclature

b	=	source width
B_o	=	source buoyancy flux
f	=	mixture fraction
E_o	=	entrainment coefficient, Eq. (8)
$F(y/(x-x_o))$	=	scaled cross stream distribution of $\bar{f}$ in self-preserving region
Fr_o	=	source Froude number
g	=	acceleration of gravity
ℓ_f	=	characteristic plume radii based on $\bar{f}$
ℓ_M	=	Morton length scale
ℓ_u	=	characteristic plane radii based on $\bar{u}$
M_o	=	source specific momentum flux
Re_o	=	source Reynolds number, $u_o b/\nu_o$
u	=	streamwise velocity
$U(y/(x-x_o))$	=	scaled cross stream distribution of $\bar{u}$ in self-preserving region
v	=	cross stream velocity
x	=	streamwise distance
y	=	cross stream distance
z	=	distance along slot from its midpoint
Z	=	slot length
ν	=	kinematic viscosity
ρ	=	density

Subscripts

c	=	centerline value
o	=	initial value or virtual origin location
max	=	maximum value
∞	=	ambient value

Superscripts

$\overline{(\ )}$	=	time-averaged mean value
$\overline{(\ )}'$	=	root-mean-squared fluctuating value

1. Introduction

An investigation of the structure and mixing properties of buoyant turbulent flows, typical of those found in the environment of unwanted fires, is described. The findings of the research have applications to modeling unwanted fires, to controlling the emission of radiant energy, toxic materials and soot from fires, to developing materials test codes for fire properties, and to developing fire detectors. The main emphasis of this work was on plane turbulent wall plumes because these flows are very typical of flows found in the environment of fires within structures.

Plane turbulent wall plumes are caused by sources of buoyancy along the base of flat walls. These flows are of interest because they are classical buoyant turbulent flows with numerous applications for confined natural convection processes and unwanted fires. Thus, the objective of this phase of the investigation was to extend the measurements of round buoyant turbulent plumes of Dai et al. (1994,1995a,b) and Dai and Faeth (1996), and of plane free buoyant turbulent plumes of Sangras et al. (1998) to consider plane turbulent wall plumes using similar methods. Present considerations were limited to turbulent plumes along smooth plane vertical surfaces for conditions where the streamwise buoyancy flux is conserved; this implies flow along an adiabatic wall for a thermal plume.

Present measurements emphasize fully-developed conditions far from the source where effects of source disturbances and momentum have been lost. Free line plumes become self-preserving at such conditions but adiabatic wall plumes never formally reach self-preserving behavior because the growth rate of the near-wall boundary layer and the outer plume-like region are not the same. Nevertheless, the outer plume-like region grows more rapidly than the near-wall boundary layer and eventually dominates wall plumes far from the source, where wall plumes approximate self-preserving behavior with scaling similar to free line plumes (Grella and Faeth, 1975; Liburdy and Faeth, 1978; Liburdy et al. 1999). Thus, self-preserving behavior of adiabatic wall plumes was sought in this approximate sense during the present investigation.

Past studies of turbulent adiabatic wall plumes include Grella and Faeth (1975), Lai et al. (1986), Lai and Faeth (1987) and references cited therein. Grella and Faeth (1975) used an array of small flames at the base of a smooth vertical insulated wall for their experiments and completed hot wire probe measurements of temperature and velocities. Lai et al. (1986) and Lai and Faeth (1987) reported LIF and LV measurements of adiabatic wall plumes created by gas mixtures. In both sets of experiments, however, there were questions about whether self-preserving behavior was actually achieved.

In view of these observations, the objectives of the present investigation were to measure the mean and fluctuating scalar and velocity properties of adiabatic wall plumes, emphasizing conditions in the approximate self-preserving region far from the source.

In the following, experimental methods and self-preserving scaling are described first. Results are then considered before summarizing conclusions. Additional information about the study can be found in articles, papers, reports and theses over the present report period that are summarized in Table 1 and cited in the list of references. The following description of the study is brief, more details can be found in Sangras et al. (1999a,b) which appear in Appendices A and B.

Table 1. Summary of Publications

This is a summary of archival publications, papers and reports and theses under this grant that were in print in press, submitted or presented during the report period.

Archival Publications (articles and book chapters):

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Velocity Statistics of Plane Self-Preserving Buoyant Turbulent Adiabatic Wall Plumes," J. Heat Trans., submitted.

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Mixture Fraction Statistics of Plane Self-Preserving Buoyant Turbulent Adiabatic Wall Plumes," J. Heat Trans., in press.

Sangras, R., Dai, Z. and Faeth, G.M. (1998) "Mixing Structure of Plane Self-Preserving Buoyant Turbulent Plumes," J. Heat Trans., Vol. 120, pp. 1033-1041, 1998.

Papers:

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Structure of Turbulent Adiabatic Wall Plumes Along Plane Vertical Smooth Surfaces," Proc. 6th Intl. Symp. Fire Safety Science, Poitiers, France, poster paper.

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Development of Buoyant Turbulent Plumes from Round Sources in Crossflows," Proc. 6th Intl. Symp. Fire Safety Science, Poitiers, France, poster paper.

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Mixture Fraction Statistics of Plane Self-Preserving Buoyant Turbulent Adiabatic Wall Plumes," *5th ASME/JSME Joint Thermal Engineering Conference*, San Diego, California, Paper No. AJTS99-6257.

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Structure of Self-Preserving Turbulent Adiabatic Wall Plumes," Proceedings of Annual Conference on Fire Research, NIST, Gaithersburg, MD, NISTIR 6242, 143-144.

Sangras, R., Dai, Z. and Faeth, G.M. (1999) "Velocity Statistics of Plane Self-Preserving Buoyant Turbulent Adiabatic Wall Plumes," Proc. ASME Winter Annual Meeting, Nashville, TN.

Sangras, R. and Faeth, G.M. (1999) "Starting Round Nonbuoyant Jets and Puffs and Buoyant Plumes and Thermals," Proc. 30th National Heat Transfer Conf., Pittsburgh, PA, submitted.

Reports and Theses:

Dai, Z., Sangras, R., Tseng, L.-K. and Faeth, G.M. (1998) "Mixing and Radiation Properties of Buoyant Luminous Flame Environments: I. Self-Preserving Plumes," Report No. GDL/GMF-98-02, University of Michigan, Ann Arbor.

Sangras, R. (1999) "Structure of Plane Self-Preserving Plane Buoyant Turbulent Plumes," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, in preparation.

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2. Experimental Methods

The experiments involved source flows of helium/air mixtures in still air along a smooth vertical wall. This approach provides a straightforward specification of the plume buoyancy flux and avoids problems of parasitic heat losses associated with thermal plumes. Measurements of mixture fraction statistics were carried out using laser-induced fluorescence (LIF); measurements of velocity statistics were carried out using laser velocimetry (LV).

The plumes were observed in a double enclosure contained in a large, high-bay test area. The outer enclosure was 3400 × 2000 × 3600 mm high and had porous walls parallel to the source and a porous ceiling both made of filter material. The filter material controlled room disturbances and light leakage into the test area while allowing free inflow of air and outflow of the plume (doubling the filter thickness had no effect on flow properties). After leaving the test enclosure, the plume gases were captured in a hood near the ceiling of the laboratory and subsequently exhausted using a blower.

The test plume was located at the plane of symmetry of the inner enclosure. The source slot was 9.4 mm wide and 876 mm long and was mounted at the center of a flat floor 876 mm long and 1220 mm wide. The flow/slot assembly was mounted normal to screen arrays across the opening. The smooth vertical wall was located at the side of the source slot between the outer extremities of the two end walls similar to the use of screens by Dai et al. (1994,1995a,b) for round plumes and by Gutmark and Wygnowski (1976) for plane free turbulent jets. Horizontal traversing was carried out by mounting the floor/wall assembly on linear bearings so that it could be moved by a stepping motor having 5 μm positioning accuracy. Vertical traversing was carried out by shifting the floor on the end walls. Optical access was provided by windows in the end walls.

The helium and air flows were mixed, passed through iodine beds and then through long lines (length-to-diameter ratios of 1200) to insure uniform mixing. This flow then entered a source manifold, passed through a bed of beads, a section of filter and contraction to the final slot exit.

Mixture fractions were measured using iodine LIF based on the 514 nm line of an argon-ion laser. The same arrangement as Dai et al. (1994) was used except that the laser was focused at the measuring volume. The LIF signal was calibrated at the source exit by diverting a portion of the source flow to the LIF measuring volume through a plastic tube. Effects of preferential diffusion and extinction of the laser and fluorescence signals were negligible. Experimental uncertainties (95% confidence) were smaller than 6 and 12% for mean and rms fluctuating mixture fractions (except near the edge of the flow where uncertainties were larger).

Dual-beam frequency-shifted LV was used for the velocity measurements based on the 514.5 nm line of an argon-ion laser. Vertical and horizontal orientations of the plane of the laser beams were used to find the corresponding components of mean and fluctuating velocities. The low-pass filtered output of the signal processor was sampled at equal time intervals to avoid velocity bias while frequency shifting avoided directional bias and ambiguity. Experimental uncertainties (95% confidence) were estimated to be less than 5 and 13% for mean and fluctuating velocities, respectively (except near the edge of the flow where uncertainties are larger).

3. Self-Preserving Scaling

The state relationship for density as a function of mixture fraction, assuming an ideal gas mixture, is as follows:

$$\rho = \rho_\infty / (1 - f(1 - \rho_\infty / \rho_o)) \tag{1}$$

Far from the source in the self-preserving region, f << 1, and Eq. (1) can be linearized as follows:

$$\rho = \rho_\infty + f\rho_\infty(1 - \rho_\infty / \rho_o), \qquad f \ll 1 \tag{2}$$

As discussed earlier, the approximation of self-preserving flow is adopted even though self-preservation can never be achieved due to the different streamwise growth rates of the wall layer and the plume edges. This approach is still reasonable far from the source, however, because the wall layer becomes only a small fraction of the width of the entire wall plume. Mean mixture fraction and mean streamwise velocity distributions then take the following forms (List, 1982):

$$F(y/(x - x_o)) = \bar{f} g B_o^{2/3} (x - x_o) | \rho_o - \rho_\infty | / \rho_o \tag{3}$$

$$U(y/(x - x_o)) = \bar{u} / B_o^{1/3} \tag{4}$$

where $F(y/(x-x_o)$ and $U(y/(x-x_o)$ are appropriately scaled universal fractions of mean mixture fraction and streamwise velocity in the self-preserving portion of the flow. Other mean and fluctuating properties of the flow also yield universal functions in terms of $y/(x-x_o)$ when appropriately normalized by $\bar{f}$ and $\bar{u}$ in the self-preserving region.

Assuming uniform properties at the source exit, the source momentum and buoyancy fluxes can be found as follows (List, 1982):

$$M_o = b u_o^2 \tag{5}$$

$$B_o = b u_o g | \rho_o - \rho_\infty | / \rho_\infty \tag{6}$$

In terms of these parameters,the Morton length scale becomes (List, 1982):

$$\ell_M = M_o / B_o^{2/3} \tag{7}$$

Other parameters such as characteristic Reynolds numbers, characteristic plume widths, etc., can be found in Sangras et al. (1998).

4. Results and Discussion

Two source flows (each) were used for the measurements of mixture fraction and velocity statistics, having initial source/ambient density rates of 0.500-0.770. The self-preserving regions were relatively far from the source slot, $(x-x_o)/b > 75$; therefore, the locations of virtual origins could not be distinguished from $x_o/b = 0$.

Present flows exhibited self-preserving behavior for $(x-x_o)/b > 75$ but it is also of interest to examine the development of adiabatic wall plumes toward self-preserving behavior. This can be done from the results appearing in Table 2, where characteristic flow widths for the mixture fraction and streamwise velocity distributions, $\ell_f/(x-x_o)$ and $\ell_u/(x-x_o)$ are tabulated as a function of distance from the source, $(x-x_o)/b$, for the measurements of Lai et al. (1986) and the present investigation. The progressive reduction of the normalized widths with increasing distance from the source, tending toward the value observed during the present investigation, is evident. Another interesting feature of these results is that the characteristic width of the velocity profile is generally larger than that of the mixture fraction profile, e.g., $\ell_u/\ell_f = 1.066$ in the self-preserving region. Initially this might seem odd because mass diffusivities generally are larger than kinematic viscosities (the laminar Prandtl-Schmidt number is generally less than unity) so that the mixture fraction distribution might be expected to be broader. The different behavior is caused by the wall boundary conditions where small near surface velocities cause the velocity field to thicken, compared to the large surface mixture fractions of the mixture fraction field.

Present measurements of cross stream distributions of mean mixture fractions for the two sources are illustrated in Fig. 1. The scaling parameters of Eq. (3) are used on the plot so that the value of the ordinate is $F(y/(x-x_o))$. Results for $z/Z = 0$ and $1/4$ are the same, confirming that the flow is reasonably two-dimensional. Present measurements yield universal distributions for $97 \leq (x-x_o)/b \leq 155$ and $12 \leq (x-x_o)/\ \ell_M \leq 21$ which implies self-preserving flow. These conditions correspond to characteristic Reynolds numbers of 3800-6700 which are large for an unconfined turbulent flow.

Table 2. Development of Plane Turbulent Adiabatic Wall Plumes[a]

Source	$(x-x_o)/b$	$\ell_f/(x-x_o)$	$\ell_u/(x-x_o)$
Lai et al. (1986)	10.0	0.173	0.183
	20.0	0.118	0.133
	37.5	0.093	0.108
Present (self-preserving Region)	92-156	0.076	0.081

[a]Plane turbulent adiabatic wall plumes along a smooth vertical wall in still and unstratified environments.

Measurements of $F(y/(x-x_o))$ for a variety of plane buoyant turbulent plumes have been plotted in Fig. 1 for comparison with the present measurements, as follows: results for adiabatic wall plumes from Grella and Faeth (1975) and Lai and Faeth (1987), results for isothermal wall plumes from Liburdy and Faeth (1978) and results for free line plumes from Sangras et al. (1998). The measurements of Sangras et al. (1998a)., Lai and Faeth (1987) and Liburdy and Faeth (1978) all exhibit streamwise variations of mean mixture fractions scaled for approximate self-preserving behavior; therefore, results plotted for these sources in Fig. 1 are for conditions farthest from the source. The results for free line plumes from Sangras et al. (1998), however, are best-fit averages over the self-preserving region.

Considering the three adiabatic wall plume results in Fig. 1, it is evident that the measurements of Lai and Faeth (1987) are broader than the present results and that the values of F for both Grella and Faeth (1975) and Lai and Faeth (1987) are considerably larger than present results near the wall. The larger sealed widths of mean mixture fraction distributions of the earlier measurements of adiabatic wall plumes are typical of transitional plumes, as discussed in connection with Table 2. Differences between the magnitudes of F for Grella and Faeth (1975) and the present study follow because B_o had to be found from measurments for the results Grella and Faeth (1975) and the present study follow because B_o had to be found from measurements for the results of Grella and Faeth (1975) but was known directly from the source mixture for the present flows, see Sangras et al. (1998) for more discussion of this point.

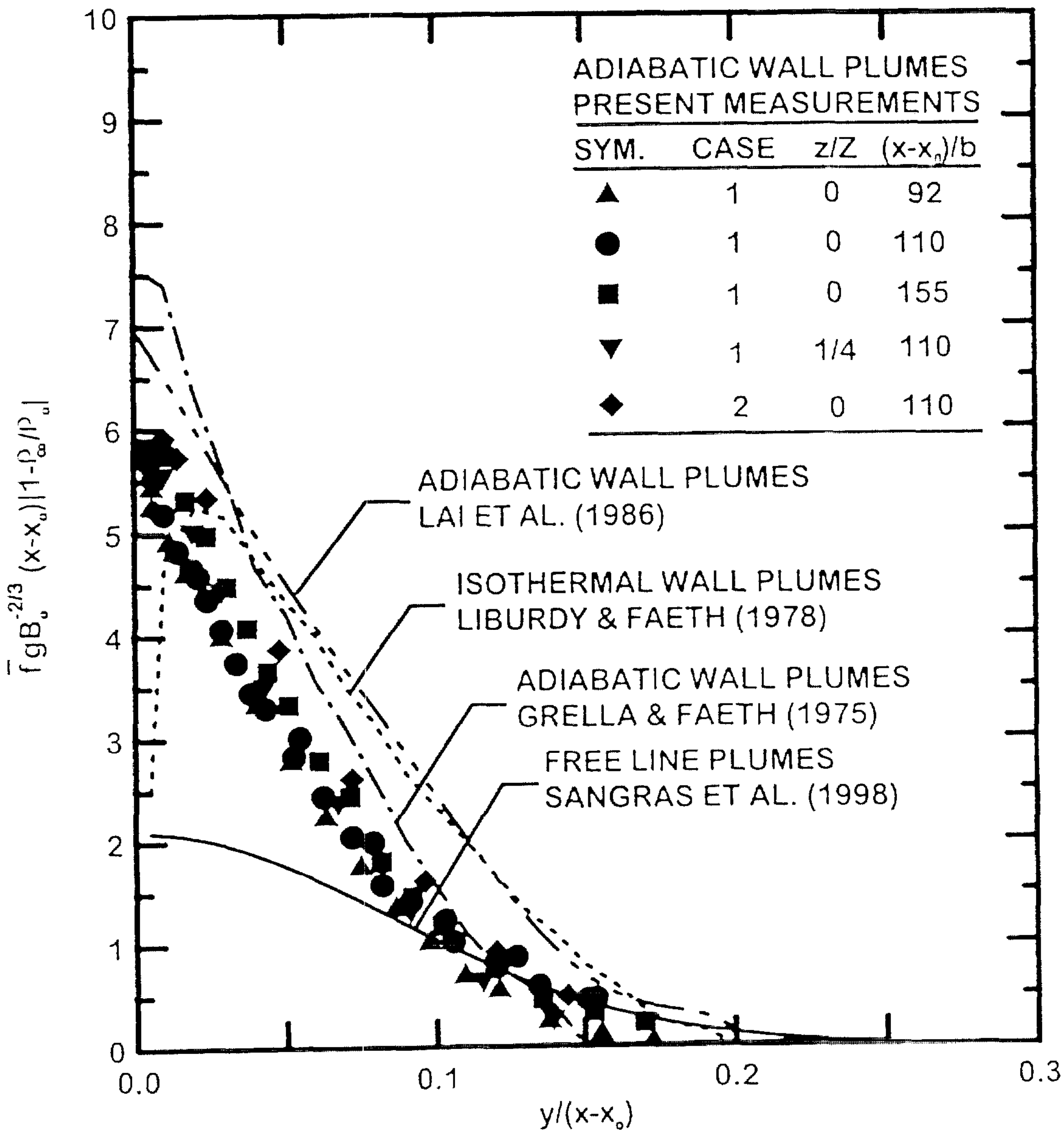

Figure 1 Cross stream profiles of mean mixture fractions in self-preserving adiabatic wall plumes.

The comparison between $F(y/(x-x_o))$ for adiabatic wall plumes and free line plumes, plotted in Fig. 1, is also of interest. Both results represent self-preserving behavior and have the same buoyancy flux but it is evident that the adiabatic wall plumes spread much slower than free line plumes, e.g., ℓ_f is 53% larger for the free line plumes spread much more slower than free line plumes, e.g., ℓ_f is 53% larger han for free line plumes and F(0) is 2.7 times larger for the adiabatic wall plumes. This behavior has undesirable implications for unwanted fires because the reduced mixing rates of adiabatic wall plumes compared to free line plumes imply that fire plumes along surfaces spread much farther from the source than would be the case for an unconfined fire. This behavior enhances fire spread rates and also reduces the rate of dilution of toxic substances within fire-caused buoyant flows.

The reduced rates of mixing for adiabatic wall plumes compared to free line plumes can be attributed to reduced access to the ambient environment, direct effects of wall friction and inhibition of turbulent mixing due to the presence of the wall. Reduced access of mixing comes about because adiabatic wall plumes only mix on one side while free line plumes mix on both sides. This effect might be expected to increase F(0) by a factor of 2; instead, F(0) increases even more, by a factor of 2.7, which suggests other effects are influencing the mixing rate. Direct effects of wall friction are small, however, as reported by Grella and Faeth (1975). Thus, the presence of the wall must reduce mixing rates in its own right, by inhibiting cross stream motion at the largest scales that significantly contribute to mixing. The isothermal wall plume results of Liburdy et al. (1979) also support this mechanism, as discussed by Sangras et al. (1998).

Present measurements of mean streamwise velocities for the two sources are illustrated in Fig. 2. The scaling parameters of Eq. (4) are used on the plot so that the value of the ordinate is $U(y/(x-x_o))$. Similar to the mixture fraction results, the measurements indicate that the flow is reasonably two-dimensional and satisfies the expectations of self-preserving behavior within experimental uncertainties for $(x-x_o)/b \geq 92$ which correspond to $(x-x_o)/\ \ell_M \geq 12$.

Measurements of $U(y/(x-x_o))$ for adiabatic wall plumes from Grella and Faeth (1975) and Lai et al. (1986) are also plotted in Fig. 2 for comparison with the present measurements. The results of Lai et al. (1986) were obtained nearer to the source than present measurements and are broader as a result due to effects of flow development as discussed earlier. The results of Grella and Faeth (1975) reach a larger peak value than the present results mainly due to underestimating B_o because the contribution of turbulence to the streamwise buoyancy flux was ignored and yet is actually 28% based on present measurements.

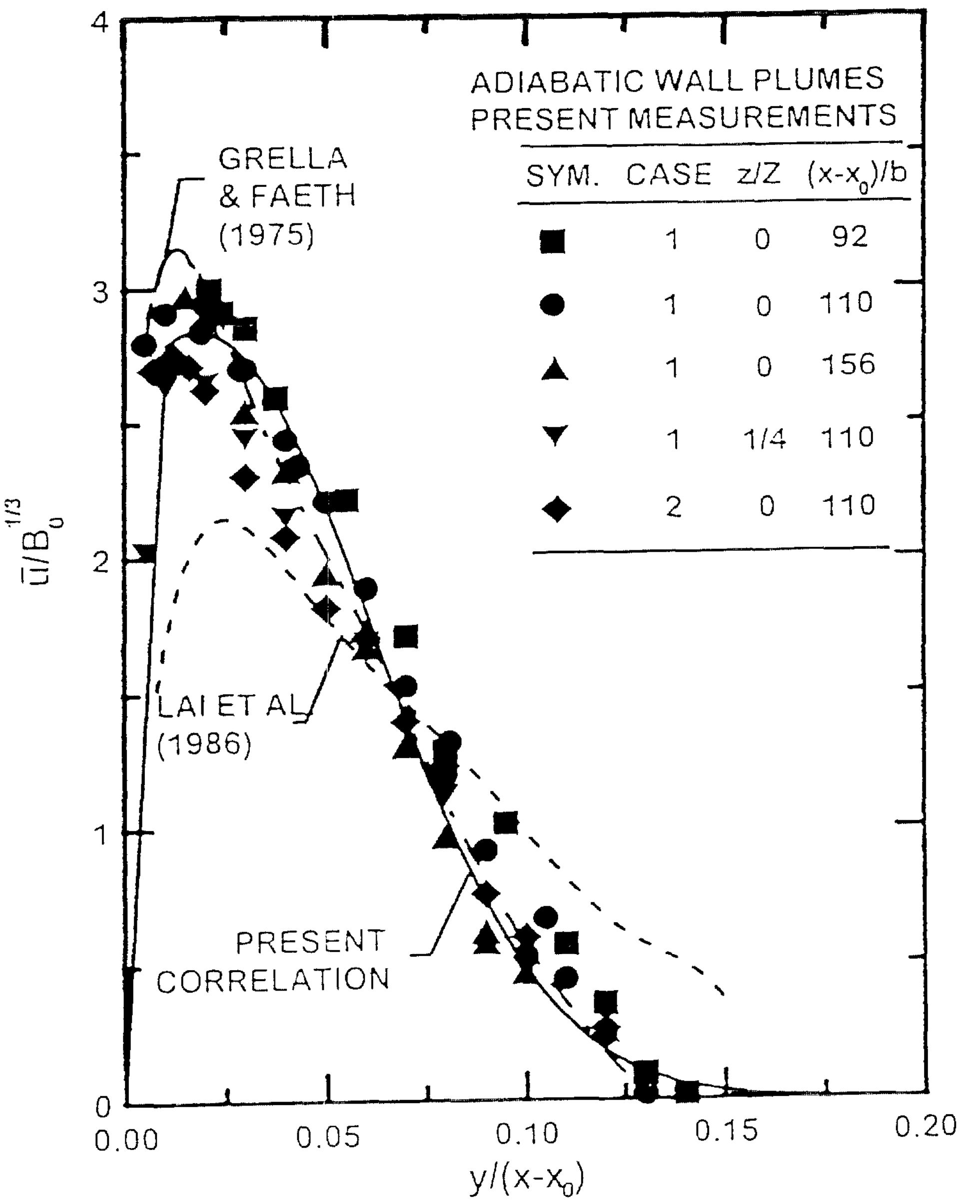

Figure 2 Cross stream profiles of mean streamwise velocities in self-preserving adiabatic wall plumes.

Present measurements of cross stream mean velocities for the two sources are illustrated in Fig. 3. Self-preserving variables have been used for this plot, similar to Fig. 2. The use of the governing equation for mean conservation of mass provides a consistency check on measurements of mean cross stream velocities; the resulting plot appears in the figure and establishes the consistency of the measurements. The asymptotic values of mean cross stream velocity at large values of $y/(x-x_o))$ are proportional to the entrainment constant of the plumes, which is important for integral theories of plume scaling and as a measure of turbulent mixing rates (Ellison and Turner, 1959; Turner 1983). The actual formula for the entrainment constant is:

$$E_o = -\bar{v}_\infty / \bar{u}_{max} \tag{8}$$

Present measurements yield $E_o = 0.068$ which is in good agreement with the early measurements of Grella and Faeth (1975).

Measurements of cross stream distributions of mixture fraction fluctuations are plotted in Fig. 4. Results plotted on this figure include findings for adiabatic wall plumes from Lai and Faeth (1987), for isothermal walls from Liburdy and Faeth (1978) and results for free line plumes from Sangras et al. (1998). As before, results for Lai and Faeth (1987) and Grella and Faeth (1975) do not extend to self-preserving conditions and only findings farthest from the source are shown while results from the present investigation represent self-preserving behavior.

Mixture fraction fluctuations for adiabatic wall plumes in Fig. 4 become smaller as the wall and free stream are approached and reach a maximum near $y/(x-x_o) = 0.02$. Values of $\bar{f}'$ for adiabatic wall plumes are larger than for free line plumes in this region, mainly because values of $\bar{f}$ are larger. In contrast, mixture fraction fluctuation intensities are larger for free line plumes than for wall plumes, 42% compared to 37%, which is consistent with the wall stabilizing turbulent motion.

Measurements of cross stream distributions of streamwise and cross stream velocity fluctuations are illustrated in Fig. 5. In addition to present measurements results from Grella and Faeth (1975), Lai et al. (1986) and Lai and Faeth (1987) are also shown on the plot. The earlier measurements do not extend to fully self-preserving conditions so that only those results farthest from the source are shown. The variables of Fig. 5 correspond to self-preserving variables for velocity fluctuations.

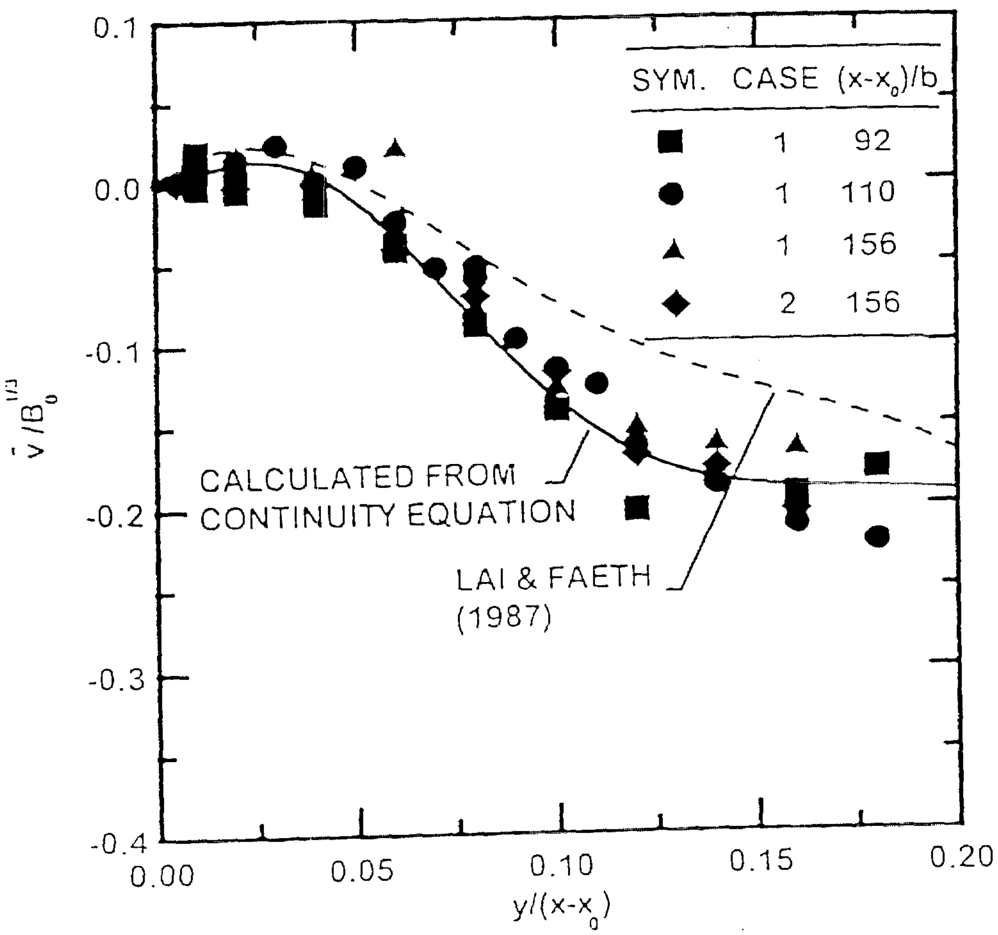

Figure 3 Cross stream profiles of mean cross stream velocities in self-preserving adiabatic wall plumes.

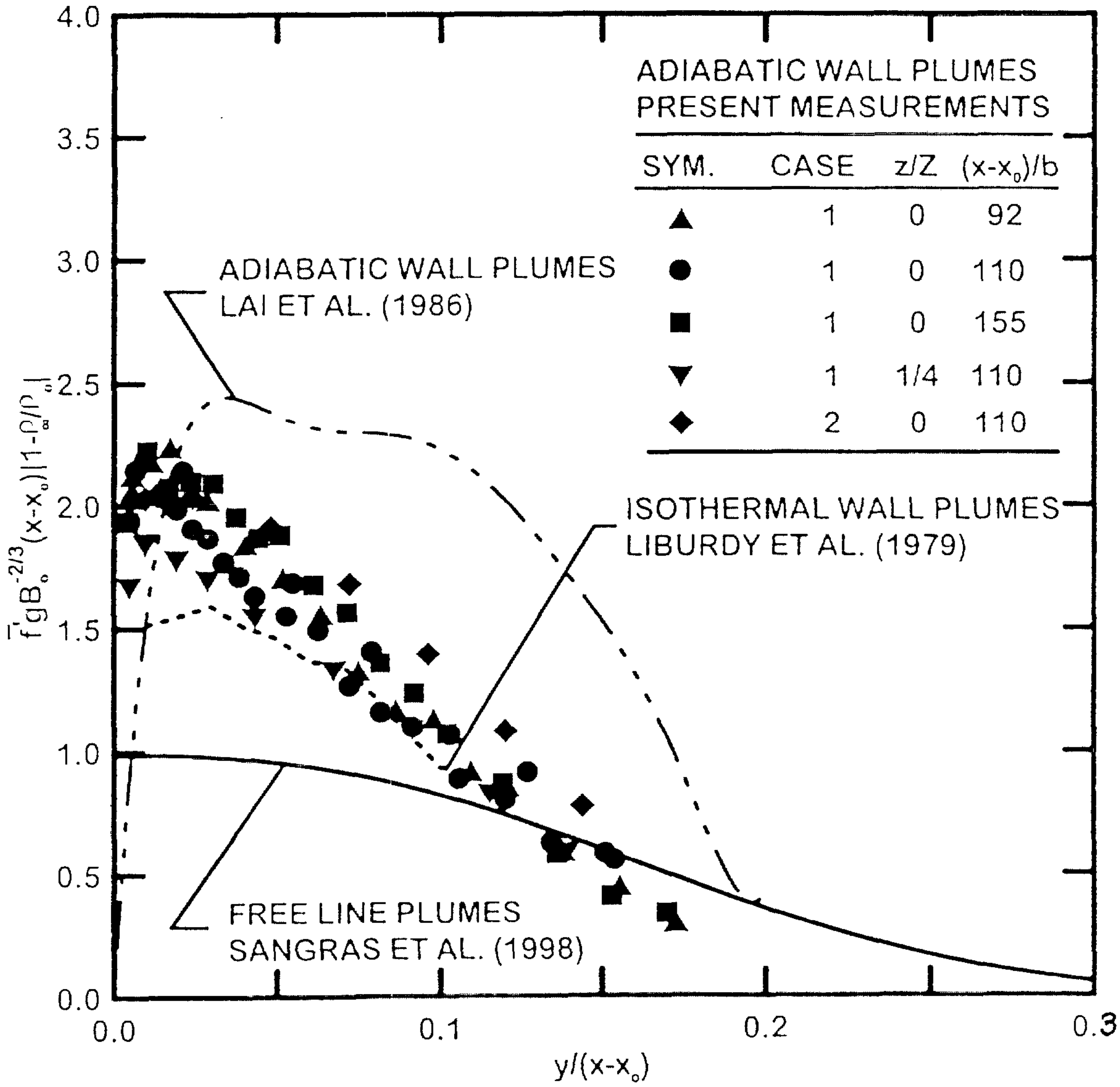

Figure 4 Cross stream profiles of rms mixture fraction fluctuations in self-preserving adiabatic wall plumes.

Present measurements of velocity fluctuations in Fig. 5 exhibit self-preserving behavior within experimental uncertainties over the test range. Maximum velocity fluctuations in adiabatic wall plumes and free line plumes, and the value of anisotropy based on maximum velocity fluctuations of 3/2, are similar. In contrast, the effect of the wall on stabilizing mixing is more apparent for mixture fraction fluctuation intensities where maximum values are larger, 47 percent, for free line plumes than for adiabatic wall plumes, 37 percent. Finally, present values of velocity fluctuations generally are larger than the earlier measurements of Grella and Faeth (1975), Lai and Faeth (1987) and Lai et al. (1986); this can be attributed to effects of flow development, along with problems of using hot wires in strongly turbulent flows serving as a contributing factor for the measurements of Grella and Faeth (1975).

Other flow properties, probability density functions and spectra, are discussed in Sangras et al. (1990a,b).

5. Conclusions

Mixture fraction and velocity statistics were measured in plane turbulent adiabatic wall plumes rising along flat smooth vertical walls in still air, emphasizing fully-developed (self-preserving) conditions. The test conditions consisted of buoyant jet sources of helium and air to give ρ_o/ρ_∞ of 0.500-0.770 with measurements extending to $(x-x_o)/b = 156$ and $(x-x_o)/\ell_M = 21$. The major conclusions of the study are as follows:

1. Present measurements yielded distributions of mean mixture fractions and velocities that approximated self-preserving behavior in the outer plume-like region of the flow for $(x-x_o)/b \geq 92$ and $(x-x_o)/\ell_M \geq 12$. In this region, distributions of mean properties were up to 22% narrower with maximum scaled values up to 75% different than earlier results in the literature. These differences were caused by past problems of completing measurements far enough from the source to reach self-preserving conditions and accurately finding the plume buoyancy flux.

2. Self-preserving turbulent adiabatic wall plumes mix much slower than comparable free line plumes, e.g., characteristic widths are 58% larger and scaled maximum mean mixture fractions are 2.7 times smaller for free line plumes than for comparable adiabatic wall plumes. These differences came about because the wall limits mixing to one side and inhibits the large-scale turbulent motion that dominates the mixing process.

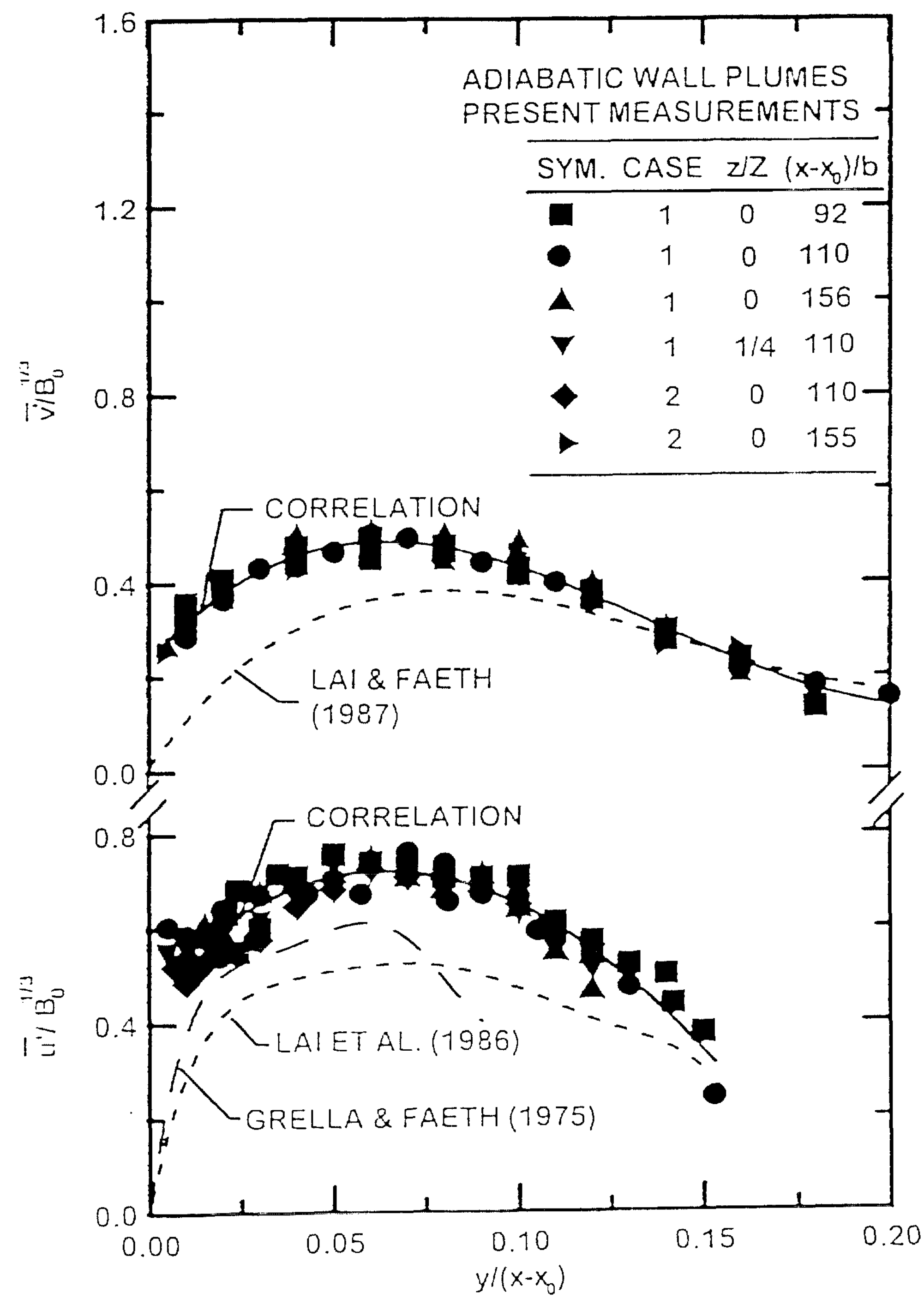

Figure 5 Cross stream profiles of rms velocity fluctuations in self-preserving adiabatic wall plumes.

3. The stabilizing effect of the wall reduces maximum mean mixture fraction fluctuation intensities in adiabatic wall plumes compared to free line plumes, e.g., the maximum intensities for the two flows are 37 and 47%, respectively. Nevertheless, turbulence/radiation interactions are much larger for adiabatic wall plumes than for free line plumes because mean mixture fractions are larger for the wall plumes for otherwise comparable conditions.

4. Cross stream distributions of velocity fluctuations are anisotropic near the maximum velocity condition ($\bar{u}'/\bar{v}' = 1.5$) with a tendency to become more isotropic near the edge of the flow. Maximum intensities of streamwise velocity fluctuations, 26 percent, are comparable to observations in free line plumes but are significantly smaller than maximum intensities of mixture fraction fluctuations, 47 percent, which are enhanced due to buoyancy/turbulence interactions. Present normalized values of velocity fluctuations are also roughly 30 percent larger than earlier observations of Lai et al. (1986) and Grella and Faeth (1975) due to problems of flow development and buoyancy flux determinations for these earlier studies that were mentioned previously.

Sangras et al. (1999a,b) should be consulted for other correlations involving probability distribution functions and power spectral densities of mixture fractions and velocities.

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Appendix A: Sangras et al. (1999a)

Mixture Fraction Statistics of Plane Self-Preserving Buoyant Turbulent Adiabatic Wall Plumes

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Measurements of the mixture fraction properties of plane buoyant turbulent adiabatic wall plumes (adiabatic wall plumes) are described, emphasizing conditions far from the source where self-preserving behavior is approximated. The experiments involved helium/air mixtures rising along a smooth, plane and vertical wall. Mean and fluctuating mixture fractions were measured using laser-induced iodine fluorescence. Self-preserving behavior was observed 92–155 source widths above the source, yielding smaller normalized plume widths and near-wall mean mixture fractions than earlier measurements. Self-preserving adiabatic wall plumes mix slower than comparable free line plumes (which have 58 percent larger normalized widths) because the wall prevents mixing on one side and inhibits large-scale turbulent motion. Measurements of probability density functions, temporal power spectra, and temporal integral scales of mixture fraction fluctuations are also reported.

Introduction

Plane turbulent wall plumes are caused by line sources of buoyancy along the base of flat walls. These flows are of interest because they are a classical buoyant turbulent flow with numerous applications for confined natural convection processes and unwanted fires. Thus, the objective of the present investigation was to extend recent measurements of turbulent round and free line plumes (Dai and Faeth, 1996; Dai et al., 1994, 1995a, b; Sangras et al., 1998) to consider plane turbulent wall plumes using similar methods. Present observations were limited to turbulent wall plumes along smooth plane vertical surfaces for conditions where the streamwise buoyancy flux is conserved, which corresponds to flow along an adiabatic wall for a thermal plume.

Present measurements emphasize fully developed conditions far from the source where effects of source disturbances and momentum have been lost. Free line plumes become self-preserving at these conditions which simplifies reporting and interpreting measurements of their properties (Tennekes and Lumley, 1972). Adiabatic wall plumes never formally approach self-preserving behavior, however, because the streamwise growth rates of the near-wall boundary layer and the outer plume-like region are not the same. Nevertheless, the outer plume-like region grows more rapidly than the near-wall boundary layer and eventually dominates wall plumes far from the source, where wall plumes approximate self-preserving behavior with scaling similar to free line plumes (Grella and Faeth, 1975; Liburdy and Faeth, 1978). Thus, self-preserving behavior of adiabatic wall plumes was sought in this approximate sense during the present investigation.

Ellison and Turner (1959) and Turner (1973) describe some of the earliest studies of wall plumes, considering adiabatic wall plumes consisting of saline solutions in still water. The entrainment rates that they observed for wall plumes were much smaller than those observed for turbulent free line plumes by Rouse et al. (1952) and Lee and Emmons (1961). This behavior was attributed to the wall both preventing mixing on one side and inhibiting the cross stream turbulent motion needed for effective mixing.

Grella and Faeth (1975) report hot-wire probe measurements of velocities and temperatures in weakly buoyant turbulent adiabatic wall plumes along smooth vertical surfaces. A linear array of small flames was used for the buoyant source; therefore, source dimensions are hard to define and plume buoyancy fluxes are difficult to quantify due to near-source heat losses. The measurements suggest that approximate self-preserving behavior was approached but could not be achieved due to the limited dynamic range of hot-wire probes. Ljuboja and Rodi (1981) subsequently predicted the properties of these flows using a turbulence model that included effects of buoyancy/turbulence interactions. The agreement between predictions and measurements was reasonably good for conditions farthest from the source which best approached approximate self-preserving behavior.

Lai et al. (1986) and Lai and Faeth (1987) reported laser velocimetry (LV) and laser-induced fluorescence (LIF) measurements of mean and fluctuating velocities and concentrations in weakly buoyant adiabatic wall plumes. Gas mixtures leaving a slot provided the buoyancy source so that uncertainties of source sizes and heat losses were absent and source dimensions and buoyancy fluxes were well defined. These measurements were used to evaluate predictions based on simplified mixing length and turbulence models, finding good predictions of mean properties but relatively ineffective predictions of turbulence properties. These measurements were limited to flow development at near-source conditions, $0 \le (x - x_o)/b \le 37.5$, so that self-preserving behavior was not achieved. This behavior is consistent with recent measurements of turbulent free line plumes where self-preserving behavior was only observed for $(x - x_o)/b > 76$ (Sangras et al., 1998).

In addition to large values of $(x - x_o)/b$ to avoid effects of source disturbances, approximate self-preserving behavior also requires large values of $(x - x_o)/l_M$ to avoid effects of source momentum (Turner, 1973). Noting that plume behavior dominates adiabatic wall plumes at self-preserving conditions, l_M can be defined by analogy to free line plumes having uniform source properties, as follows (List, 1982):

$$l_M/b = (\rho_o/\rho_\infty)u_o^3/(bu_o g|\rho_o - \rho_\infty|/\rho_\infty)^{2/3} \qquad (1)$$

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where the absolute value of the initial density difference is used to account for both rising and falling plumes. A related parameter used to characterize source momentum properties is the source Froude number, Fr_o, defined for adiabatic wall plumes by analogy to free line plumes, as follows:

$$Fr_o^2 = \rho_o u_o^2 / (2bg|\rho_\infty - \rho_o|). \tag{2}$$

Using these parameters, the measurements of Lai et al. (1986) and Lai and Faeth (1987) were limited to $(x - x_o)/l_M \leq 5$ which is small compared to the values on the order of 10 required for buoyancy-dominated self-preserving behavior for free line plumes (Sangras et al., 1998).

In view of these observations, the objective of the present investigation was to measure the mean and fluctuating scalar properties of adiabatic wall plumes, emphasizing conditions within the approximate self-preserving region far from the source. The experiments consisted of helium/air source flows, along a smooth plane and vertical wall in still air at standard temperature and pressure, which provides straightforward specifications of source dimensions and plume buoyancy fluxes. Scalar properties were characterized by mixture fractions, defined as the mass fraction of source gas in a sample (Sangras et al., 1998). Measurements of mixture fractions were carried out using iodine vapor LIF in order to provide the large dynamic range needed to reach approximate self-preserving conditions.

Experimental Methods

Apparatus. Experimental methods were similar to the free line plume study of Sangras et al. (1998). The plumes were observed in an enclosure (3400 × 2000 × 3600 mm high) that had porous side walls (parallel to the source) and a porous ceiling made of filter material. This approach controlled room disturbances and ambient light leakage into the test enclosure while allowing free inflow of entrained air and free exhaust of the plume. The source slot (876 mm long × 9.4 mm wide) was mounted flush to a flat floor (876 mm long × 610 mm wide) with the vertical wall mounted adjacent to one edge of the slot. The floor/slot/wall assembly was mounted in turn normal to end walls (2440 mm high × 610 mm wide). A screen array (2 screens, 16 mesh × 0.20 mm wire diameter, separated by a distance of 38 mm) was installed across the outer edge of the end walls (facing the vertical wall) to further control room disturbances, following Gutmark and Wygnanski (1976), Sangras et al. (1998) and references cited therein. The entire floor/slot/wall assembly was traversed to accommodate rigid optical instruments in the same manner as Sangras et al. (1998).

Gas supplies to the source were metered and measured using critical flow orifices in conjunction with pressure regulators. These flow rates were calibrated using either wet test or turbine flow meters. After mixing, the source flows passed through beds of iodine flakes and feed lines having length-to-diameter ratios of 1200 to ensure uniformly seeded mixtures. Uniform source flow properties were provided by a bed of beads, a filter and a 3.4:1 contraction at the slot exit.

Instrumentation. The LIF signal was produced by an argon-ion laser operating at 514.5 nm (measuring volume diameter at e^{-2} points of 0.16 mm with a maximum optical power of 1800 mW). The laser beam was horizontal and directed normal to the wall. The beam passed through an opening in the wall and was captured by a horn trap. Laser power was monitored to correct for power fluctuations. Absorption of the laser beam in the flow was less than one percent, and was even smaller for fluorescence emissions, so that it was not necessary to account for effects of absorption when data was processed.

LIF observations were made through windows (457 mm wide × 203 mm high) mounted flush to the inner surface of the end walls and centered on the laser beam height. Collecting optics were f5.1 with a diameter of 100 mm. The LIF signal was separated from light scattered at the laser line using long-pass optical filters having a cutoff wavelength of 530 nm. The detector aperture provided a measuring volume length of 2 mm. Signal detection, processing, and calibration were the same as Sangras et al. (1998).

Effects of differential diffusion of helium and iodine vapor were small, less than 0.1 percent, based on binary diffusivity estimates from Bird et al. (1960) and the analysis of Stårner and Bilger (1983). Gradient broadening errors were also small, less than one percent. Experimental uncertainties (95 percent confidence) were found following Moffat (1982) as discussed by Sangras et al. (1998), yielding maximum experimental uncertainties of the flow properties, as follows: 6 percent for $F(y/(x - x_o))$, 10 percent for $F'(y/(x - x_o))$, 10 percent for PDF(f), 40 percent for the low-frequency region of $E_f(n)/(\tau_f \bar{f}'^2)$, and 35 percent for $B_o^{1/3}\tau_f/$

Nomenclature

- b = source width
- B_o = source buoyancy flux
- d = source diameter
- $E_f(n)$ = temporal power spectral density of f
- f = mixture fraction
- $F(y/(x - x_o))$ = normalized self-preserving cross stream distribution of $\bar{f}$
- $F'(y/(x - x_o))$ = normalized self-preserving cross stream distributions of $\bar{f}'$
- Fr_o = source Froude number, Eq. (2)
- g = acceleration of gravity
- l_f = characteristic plume width based on $\bar{f}$, Eq. (5)
- l_M = Morton length scale, Eq. (1)
- l_u = characteristic plume width based on $\bar{u}$, Eq. (8)
- n = frequency
- PDF(f) = probability density function of mixture fraction
- Re_c = characteristic plume Reynolds number, Eq. (9)
- Re_o = source Reynolds number, $2\bar{u}_o b/\nu_o$
- u = streamwise velocity
- $U(y/(x - x_o))$ = normalized self-preserving cross stream distribution of $\bar{u}$
- x = vertical streamwise distance above source
- y = cross stream distance normal to wall surface
- z = normalized distance parallel to slot source, measured from its midplane location
- Z = source length
- ν = kinematic viscosity
- ρ = density
- τ_f = temporal integral scale of mixture fraction fluctuations

Subscripts

- max = condition where the property reaches a maximum value
- o = initial value or virtual origin location
- ∞ = ambient value

Superscripts

- $(\bar{\ })$ = time-averaged mean value
- $(\bar{\ })'$ = root-mean-squared fluctuating value

Table I Summary of plane buoyant turbulent adiabatic wall plume test conditions[a]

Source properties	Case 1	Case 2
Helium concentration (percent by volume)	29.0	52.3
Density (kg/m^3)	0.871	0.639
Kinematic viscosity (mm^2/s)	22.1	31.3
Average velocity (mm/s)	868	1240
Buoyancy flux, B_o (m^3/s^3)	0.0200	0.0514
Density ratio, ρ_o/ρ_∞	0.750	0.550
Reynolds number, Re_o	740	745
Froude number, Fr_o	3.50	3.20
Morton length scale, l_M/b	7.7	6.1

[a] Helium/air sources directed vertically upward at the base of a vertical smooth plane wall in still air with an ambient pressure of 99 ± 0.5 kPa and temperature of 297 ± 0.5 K. Pure gas properties as follows: air density of 1.161 kg/m^3, air kinematic viscosity of 15.9 mm^2/s, helium density of 0.163 kg/m^3, and helium kinematic viscosity of 122.5 mm^2/s. Source slot width and length of 9.4 and 876 mm. Virtual origin based on $\bar{f}$ of $x_o/b = 0$ determined from present measurements in the range $(x - x_o)/b = 92$–155 and $(x - x_o)/l_M = 12$–21.

$(x - x_o)$. These uncertainties were maintained down to half the maximum value of each measured parameter (excluding the spike region of the PDF) but increased at smaller values roughly inversely proportional to the value of the parameter.

Test Conditions. The test conditions are summarized in Table 1. Two source flows were considered in order to test scaling of source properties in the region of self-preserving behavior. Approximate self-preserving behavior for adiabatic wall plumes was only observed relatively far from the source at $(x - x_o)/b \geq 92$; therefore, the locations of the virtual origin could not be distinguished from $x_o/b = 0$ within present experimental uncertainties.

Self-Preserving Scaling

The state relationship for density as a function of mixture fraction, assuming an ideal gas mixture, can be found in Dai et al. (1994). Far from the source where the flow becomes self-preserving, this expression can be approximated as follows:

$$\rho = \rho_\infty + f\rho_\infty(1 - \rho_\infty/\rho_o),\ f \ll 1. \qquad (3)$$

Assuming approximate self-preserving behavior for adiabatic wall plumes, in the sense discussed earlier, mean and fluctuating mixture fractions can be scaled in terms of self-preserving variables, as follows (List, 1982):

$$F(y/(x - x_o)) \quad \text{or} \quad F'(y/(x - x_o))$$
$$= (\bar{f} \text{ or } \bar{f}')gB_o^{-2/3}(x - x_o)|1 - \rho_\infty/\rho_o| \quad (4)$$

where $F(y/(x - x_o))$ and $F'(y/(x - x_o))$ are appropriately scaled cross stream profile functions of mean and fluctuating mixture fractions, which approximate universal functions far from the source where Eq. (3) applies. A characteristic plume width, l_f, based on $\bar{f}$ is also defined, similar to turbulent free line plumes, as follows (Dai et al., 1994):

$$F(l_f/(x - x_o))/F(0) = e^{-1}. \qquad (5)$$

For plane turbulent adiabatic wall plumes, F decreases monotonically as y increases and there is only one location where Eq. (5) is satisfied. The source buoyancy flux, B_o, is a conserved scalar of the flow which can be found as follows for plane plumes having uniform source properties (List, 1982):

$$B_o = bu_o g|\rho_o - \rho_\infty|/\rho_\infty. \qquad (6)$$

The corresponding approximate self-preserving relationship for mean streamwise velocities was not studied here but these properties are useful for defining the turbulence properties of the wall plumes. Thus, mean streamwise velocities within approximate

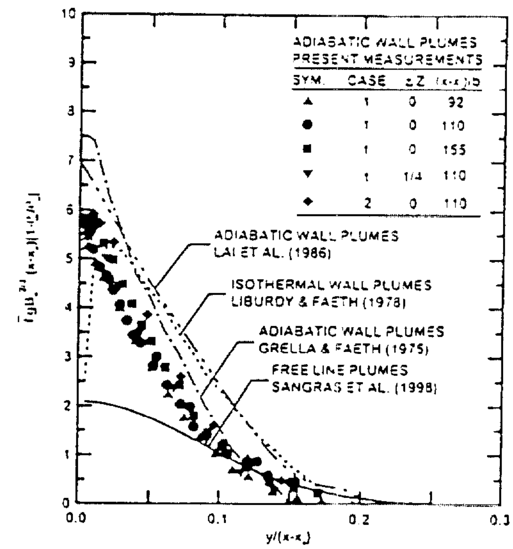

Fig. 1 Cross stream distributions of mean mixture fractions in plane buoyant turbulent plumes. Measurements of Grella and Faeth (1975), Lai and Faeth (1987), and the present investigation for adiabatic wall plumes; measurements of Liburdy and Faeth (1978) for isothermal wall plumes; and measurements of Sangras et al. (1998) for free line plumes. Results from Grella and Faeth (1975), Liburdy and Faeth (1978), and Lai and Faeth (1987) are for their largest distances from the source.

self-preserving turbulent adiabatic wall plumes can be scaled in terms of self-preserving variables, as follows (List, 1982):

$$U(y/(x - x_o)) = \bar{u}/B_o^{1/3} \qquad (7)$$

where $U(y/(x - x_o))$ is an appropriately scaled cross stream profile function. A characteristic plume width based on $\bar{u}$, l_u, is also defined, similar to turbulent free line plumes, as follows (Dai et al., 1995a):

$$U(l_u/(x - x_o))/U_{max} = e^{-1} \qquad (8)$$

where l_u is the largest value of cross stream distance where Eq. (8) is satisfied, noting that U is a double-valued function of y. The corresponding characteristic plume Reynolds number can be written as follows for approximate self-preserving conditions (Sangras et al., 1998):

$$Re_c = \bar{u}_{max}l_u/\nu_\infty = U_{max}B_o^{1/3}l_u/\nu_\infty. \qquad (9)$$

For present purposes, values of U_{max} and l_u were taken as averages of the measurements farthest from the source reported by Grella and Faeth (1975).

Results and Discussion

Mean Mixture Fractions. Distributions of mean mixture fractions in the approximate self-preserving region of the flow will be considered first. Present measurements of cross stream distributions of mean mixture fractions for the two sources are illustrated in Fig. 1. The scaling parameters of Eq. (4) have been used when plotting the figure so that the value of the ordinate is $F(y/(x - x_o))$. Results for $z/Z = 0$ and $\frac{1}{4}$ (where z is measured from a position halfway between the end walls), are in good agreement with each other which confirms the two-dimensionality of the flow. The present measurements also yield universal distributions within experimental uncertainties for $92 \leq (x - x_o)/b \leq 155$ and $12 \leq (x - x_o)/l_M \leq 21$ with flow aspect ratios of $Z/l_f \geq 7.9$, as required for self-preserving flow. Present conditions within the self-preserving region of the flow correspond to $3800 \leq$

Table 2 Development of plane turbulent adiabatic wall plumes*

Source	$(x - x_o)/b$	$l_f/(x - x_o)$
Lai et al. (1986)	10.0	0.173
	20.0	0.118
	37.5	0.093
Present (self-preserving region)	92–155	0.076

*Plane turbulent adiabatic wall plumes in still and unstratified environments.

$Re_c \leq 6700$ which is comparable to conditions within the self-preserving region of round and plane free turbulent plumes of $2500 \leq Re_c \leq 7500$ observed by Dai et al. (1994, 1995a,b) and Sangras et al. (1998). These are reasonably large values of characteristic Reynolds numbers for turbulent plume-like flows. For example, this range is comparable to the largest values of Re_c where measurements of turbulent wake properties have been reported, while turbulent wakes exhibit self-preserving turbulence properties at values of Re_c as small as 70 (Wu and Faeth, 1993).

Measurements of F for a variety of plane turbulent plumes have been plotted in Fig. 1 for comparison with the present measurements, as follows: results for adiabatic wall plumes from Grella and Faeth (1975) and Lai and Faeth (1987), results for isothermal wall plumes from Liburdy and Faeth (1978), and results for free line plumes from Sangras et al. (1998). The measurements of Grella and Faeth (1975), Lai and Faeth (1987), and Liburdy and Faeth (1978) all exhibit streamwise variations of mean mixture fractions scaled for approximate self-preserving behavior; thus, the distributions plotted in Fig. 1 for these measurements are for conditions farthest from the source. The remaining results from Sangras et al. (1998) and the present study represent scaled mean mixture fractions averaged over the self-preserving portions of the plumes.

Considering the three adiabatic wall plume results in Fig. 1, it is evident that the measurements of Lai and Faeth (1987) are considerably broader than the present results (22 percent broader at the e^{-1} points of the distributions) and that the values of F for both Grella and Faeth (1975), and Lai and Faeth (1987) are considerably larger than the present results near the wall (up to 31 percent larger). The larger scaled widths of the mean mixture fraction distributions of the earlier adiabatic wall plumes are typical of conditions in the developing plume region before self-preserving behavior is achieved. Developing flow was especially evident for the measurements of Lai and Faeth (1987) which were limited to $(x - x_o)/b \leq 37.5$ while self-preserving behavior was only observed much farther from the source $(x - x_o)/b \geq 92$, during the present investigation. This behavior is illustrated by the values of $l_f/(x - x_o)$ summarized in Table 2 for the measurements of Lai et al. (1986) and the present investigation. The progressive reduction of $l_f/(x - x_o)$ with increasing distance from the source, tending toward the value observed during the present investigation, is quite evident. The corresponding streamwise locations of the measurements of Grella and Faeth (1975) cannot be stated in terms of $(x - x_o)/b$ because their source dimensions are not well defined; nevertheless, it is encouraging that the characteristic width of these measurements at the largest distance from the source is in good agreement with the present measurements.

Differences between the magnitudes of the scaled mean mixture fraction measurements of Grella and Faeth (1975) and the present investigation can be attributed to problems of specifying the buoyancy flux, B_o, for the measurements of Grella and Faeth (1975). In particular, B_o was accurately prescribed by the gas mixture at the source exit for the present study but B_o had to be obtained from measurements of plume velocity and temperature properties for the study of Grella and Faeth (1975) due to the difficulties of determining energy losses from thermal plumes near the source. This approach introduces significant uncertainties in B_o, particularly because a significant portion of B_o is transported by streamwise turbulent motion, e.g., Dai et al. (1995b) and George et al. (1977) find that streamwise turbulent transport contributes 15–16 percent of B_o for round buoyant turbulent plumes with similar levels anticipated for plane turbulent plumes. The streamwise transport contribution to B_o was not measured by Grella and Faeth (1975) and had to be ignored so that the corresponding underestimation of B_o tends to increase values of F compared to present results as seen in Fig. 1.

The comparison between the distributions of F for adiabatic wall plumes and free line plumes, plotted in Fig. 1, is also of interest. Both sets of results represent self-preserving behavior and have the same buoyancy flux. Comparing the two flows, it is evident that the adiabatic wall plumes spread much slower than the free line plumes. For example, the characteristic widths, l_f, are 58 percent larger for the free line plumes than for the adiabatic wall plumes whereas the maximum scaled mean mixture fraction, $F(0)$, is 2.7 times larger for adiabatic wall plumes than for the free line plumes. This behavior has unfortunate implications for the environment of unwanted fires within structures where the reduced mixing rates of fire plumes along surfaces allow heated regions to extend much farther from the source than would be the case for unconfined fires; this behavior tends to enhance fire spread rates. These effects also tend to reduce dilution rates of pollutants and other hazardous substances within buoyant flows along surfaces compared to unconfined buoyant flows.

Reduced rates of mixing of adiabatic wall plumes compared to free line plumes can be attributed to reduced access to the ambient environment, the direct effects of wall friction and inhibition of turbulent mixing by the presence of the wall. The reduced access to the ambient environment comes about because adiabatic wall plumes can only mix on one side while free line plumes can mix on both sides. This effect might be expected to increase the maximum scaled mean mixture fraction, $F(0)$, by a factor of 2; instead, $F(0)$ increases even more, by a factor of 2.7, which suggests that other effects are influencing mixing rates as well. The direct effect of wall friction, however, does not explain any significant tendency to retard mixing rates for adiabatic wall plumes. For example, earlier studies of adiabatic wall plumes show the direct effects of wall friction on plume structure are small because the wall boundary layer is much thinner than the outer plume-like region as self-preserving conditions are approached (Grella and Faeth, 1975; Lai et al., 1986; Lai and Faeth, 1987). Thus, the presence of the wall must reduce mixing in its own right, probably by inhibiting cross stream turbulent motion at the largest scales that significantly contribute to the mixing of free line plumes.

Results for isothermal wall plumes due to Liburdy and Faeth (1978) plotted in Fig. 1 also support the idea that the main functions of the wall are to limit mixing to just one side of the plume and to inhibit turbulent motion at the largest scales which tends to reduce mixing rates. In particular, Liburdy and Faeth (1978) find little effect of direct transport to the wall on reducing values of F as self-preserving conditions are approached (although wall heat losses near the source are very important for these thermal plumes). On the other hand, wall heat losses shift the maximum value of F away from the wall, tending to increase the thickness of the flow. This increased thickness accommodates larger scales of turbulence which increases mixing rates as evidenced by the smaller F_{max} for isothermal wall plumes than for adiabatic wall plumes.

The differences between the various flows plotted in Fig. 1 are quantified in Table 3, where the aspect ratio of the slot, Z/b, the range of streamwise distances studied $(x - x_o)/b$, the smallest flow aspect ratios, $(Z/l_f)_{min}$, the streamwise distance in terms of Morton length scale, $(x - x_o)/l_M$, and the corresponding values of $l_f/(x - x_o)$, F_{max} and $\bar{f}_{max}/f_{max}$ are summarized to the extent they are known for adiabatic wall plumes, isothermal wall plumes, and free line plumes. Earlier results for wall plumes exhibit some evolution of F with distance from the source over the range of the measurements; therefore, only findings farthest from the source are shown in the table in these cases. The measurements of Grella and

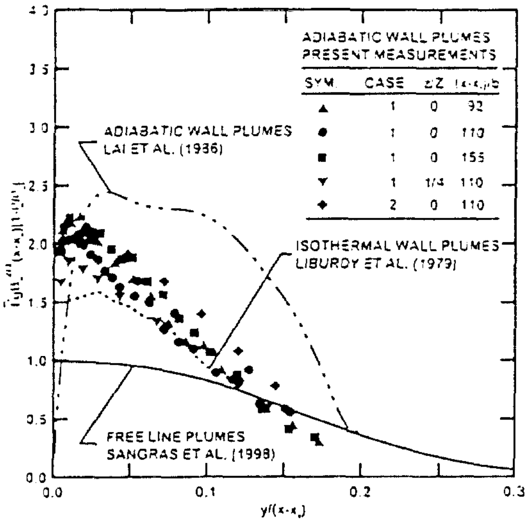

Fig. 2 Cross stream distributions of rms mixture fraction fluctuations in plane buoyant turbulent plumes. Measurements of Lai and Faeth (1987) and the present investigation for adiabatic wall plumes; measurements of Liburdy and Faeth (1978) for isothermal wall plumes; and measurements of Sangras et al. (1998) for free line plumes. Results from Liburdy and Faeth (1978) and Lai and Faeth (1987) are for their largest distances from the source.

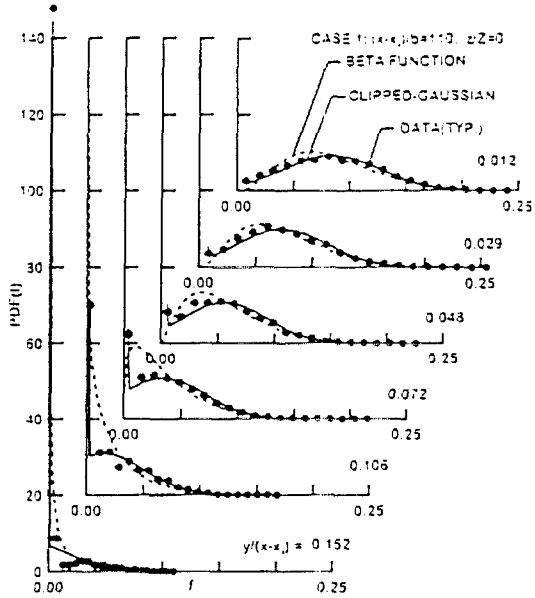

Fig. 3 Typical probability density functions in plane self-preserving buoyant turbulent adiabatic wall plumes: Case 1 flow at $(x - x_o)/b = 110$

Faeth (1975), Liburdy and Faeth (1978) and Liburdy et al. (1979) employed linear arrays of small flames as thermal sources for the plumes so that source dimensions cannot be prescribed for these results. Variations of flow widths and values of F between the various flows have already been discussed in connection with Fig. 1; the properties of mixture fraction fluctuations will be taken up next.

Mixture Fraction Fluctuations. Measurements of cross stream distributions of mixture fraction fluctuations are plotted in Fig. 2. In addition to the present measurements for the same conditions as $\bar{f}$ in Fig. 1, other measurements have been plotted in the figure, as follows: adiabatic wall plumes from Lai and Faeth (1987), isothermal wall plumes from Liburdy and Faeth (1978), and free line plumes from Sangras et al. (1998). As before, the measurements of Lai and Faeth (1987) and Liburdy and Faeth (1978) do not extend to fully self-preserving conditions so that only their results farthest from the source are shown. The remaining results from Sangras et al. (1998) and the present study represent scaled mixture fraction fluctuations in the self-preserving portions of the flow.

Present measurements of F' exhibit self-preserving behavior within experimental uncertainties over the test range. F' becomes small as the wall and the free stream are approached and reaches a maximum near $y/(x - x_o) = 0.02$. The values of $\bar{f}'$ are actually larger for adiabatic wall plumes near this maximum than the values observed in free line plumes at similar conditions because the values of $\bar{f}$ in this region are larger for adiabatic wall plumes than for free line plumes. The values of mixture fraction fluctuation intensities near the maximum $\bar{f}$ condition, however, are actually smaller for adiabatic wall plumes than for free line plumes, e.g., 37 percent as opposed to 47 percent, see Table 3, which is consistent with the wall stabilizing large-scale turbulent motion, and thus turbulent mixing. The adiabatic wall plume results of Lai and Faeth (1987) are similar to present results in terms of magnitudes, e.g., the values of $\bar{f}'_{max}/\bar{f}_{max}$ for the two studies are 34 and 37 percent, respectively. The distribution of F' is considerably broader for the measurements of Lai and Faeth (1987) than the present study, however, which follows because self-preserving conditions were not reached, as noted earlier. The measurements of Liburdy et al. (1979) for isothermal wall plumes are considerably smaller than the other wall plumes for reasons that have yet to be explained; values of $\bar{f}'_{max}/\bar{f}_{max}$ for this flow are also lower than for all the other plumes, e.g., 25 percent, see Table 3.

Probability Density Functions. The measured PDF(f) are illustrated in Fig. 3 for self-preserving adiabatic wall plumes. These results are for the Case 1 source at various cross stream distances and $(x - x_o)/b = 110$ but results at other self-preserving conditions were similar. The measurements are compared with predictions of clipped-Gaussian and beta function distributions which frequently are used to represent PDF(f) for modeling purposes (Lockwood and Naguib, 1975). These distributions are prescribed by the values of $\bar{f}$ and $\bar{f}'$ at each position.

The PDF(f) illustrated in Fig. 3 exhibit progressively increasing spikes at $f = 0$ as $y/(x - x_o)$ increases, representative of increasing time periods spent in ambient fluid as the outer edge of the flow is approached. Both distributions provide a reasonably good representation of the measured PDF's. All these properties are similar to earlier findings for free line plumes (Sangras et al., 1998).

Temporal Power Spectral Densities. Typical temporal power spectra are illustrated in Fig. 4 for self-preserving adiabatic wall plumes. These results are for $92 \leq (x - x_o)/b \leq 155$ with the Case 1 plume but results for other self-preserving conditions are similar. These measurements are normalized by local turbulence properties as described by Hinze (1975).

These spectra are qualitatively similar to earlier results for round plumes reported by Dai et al. (1994) and for free line plumes reported by Sangras et al. (1998). The normalized spectra are relatively independent of cross stream position at each streamwise location. The spectra exhibit a prominent $-5/3$ power decay in an inertial-convective subrange for scalar property fluctuations where effects of molecular diffusion are small (Tennekes and Lumley, 1972) followed by a prominent -3 power decay in an inertial-diffusion subrange for scalar property fluctuations where effects of molecular diffusion are significant (Papanicolaou and List, 1987). The latter region is not observed in nonbuoyant flows and represents an important buoyancy/turbulence interaction.

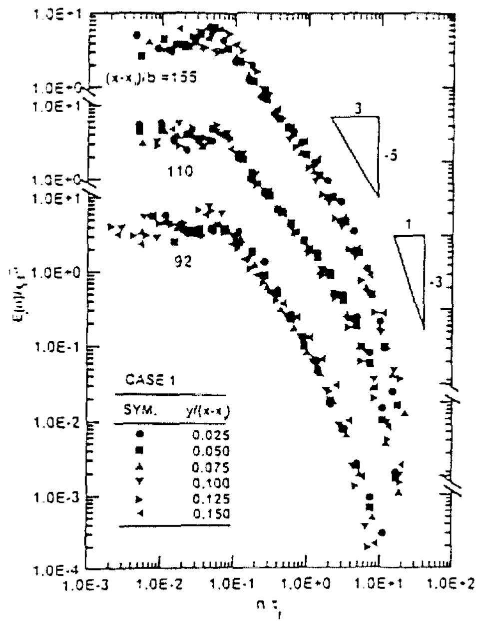

Fig. 4 Typical temporal power spectral densities of mixture fraction fluctuations in plane self-preserving buoyant turbulent adiabatic wall plumes: Case 1 flow at $(x - x_o)/b$ = 92, 110, and 155

Temporal Integral Scales. The properties of the temporal power spectra are completed by temporal integral scales, which are plotted as a function of cross stream distance in Fig. 5. These measurements are limited to the case 1 source for $92 \le (x - x_o)/b \le 155$, however, results at other self-preserving conditions are similar. The correlation for the temporal integral scales of self-preserving free line plumes from Sangras et al. (1998) is also shown in the plot for comparison with the present results. The present results provide a scattered correlation when plotted in the manner of Fig. 5; nevertheless, these results agree with the free line plume results within experimental uncertainties in spite of increased width of free line plumes. The shape of the plot generally agrees with expectations for temporal integral scales based on Taylor's hypothesis, as discussed by Sangras et al. (1998).

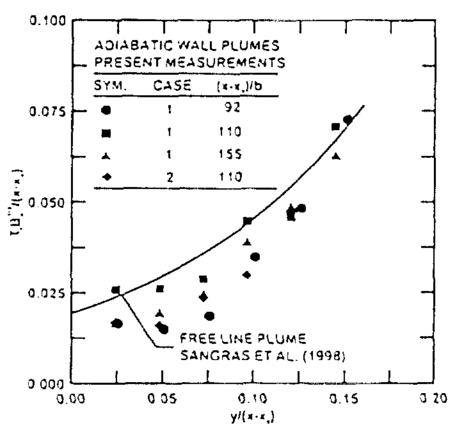

Fig. 5 Cross stream distributions of temporal integral scales of mixture fraction fluctuations in plane self-preserving buoyant turbulent plumes. Measurements of the present investigation for adiabatic wall plumes; measurements of Sangras et al. (1998) for free line plumes.

Conclusions

Mixture fraction statistics were measured in plane turbulent adiabatic wall plumes rising along flat smooth vertical walls in still air. Conditions far from the source were emphasized where effects of source disturbances are lost and the outer plume-like region of the flow approximates self-preserving behavior with scaling similar to self-preserving free line plumes. The test conditions consisted of buoyant jet sources of helium and air to obtain the source properties summarized in Table 1 with measurements involving $(x - x_o)/b$ in the range 92–155 and $(x - x_o)/l_M$ in the range 12–21. The major conclusions of the study are as follows:

1 The present measurements yielded distributions of mean mixture fractions that approximated self-preserving behavior in the outer plume-like region of the flow for $(x - x_o)/b \ge 92$. In this region distributions of mean mixture fractions were up to 22 percent narrower, with scaled values at the wall up to 31 percent smaller than earlier results using buoyant jet sources in the literature. These differences were caused by past difficulties in achieving adequate distances from the source to reach self-preserving conditions and accurately determining the value of the buoyancy flux needed to scale self-preserving properties during the earlier studies.

2 Self-preserving turbulent adiabatic wall plumes mix much slower than comparable free line plumes with characteristic plume widths 58 percent larger and scaled maximum mean mixture fractions 2.7 times smaller for free line plumes than for comparable adiabatic wall plumes mainly because the wall limits mixing to one side of the flow and inhibits the large-scale turbulent motion that is mainly responsible for mixing.

3 Cross stream distributions of mixture fraction fluctuations exhibit reduced values near the wall as expected. The stabilizing effect of the wall also reduces maximum mean mixture fraction fluctuation intensities in self-preserving plane turbulent adiabatic wall plumes compared to corresponding turbulent free line plumes, e.g., the maximum intensities for the two flows are 37 and 47 percent, respectively.

4 The probability density functions of mixture fractions in self-preserving adiabatic wall plumes are approximated reasonably well by either clipped Gaussian or beta function distributions similar to corresponding free line plumes.

5 The low-frequency portion of the spectra of mixture fraction fluctuations scale in a relatively universal manner while the spectra exhibit −5/3 power inertial-convective and −3 power inertial-diffusive decay regions. This behavior is typical of other turbulent plumes with the prominent −3 power inertial-diffusive decay region being a characteristic of buoyant flows that is not seen in nonbuoyant flows.

6 Temporal integral scales could be correlated in a relatively universal manner in terms of self-preserving parameters, with results for adiabatic wall plumes in qualitative agreement with the behavior of corresponding free line plumes.

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Appendix B: Sangras et al. (1999b)

VELOCITY STATISTICS OF PLANE SELF-PRESERVING BUOYANT TURBULENT ADIABATIC WALL PLUMES

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VELOCITY STATISTICS OF PLANE SELF-PRESERVING BUOYANT TURBULENT ADIABATIC WALL PLUMES

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Abstract

Measurements of the velocity properties of plane buoyant turbulent adiabatic wall plumes (adiabatic wall plumes) are described, emphasizing conditions far from the source where self-preserving behavior is approximated. The experiments involved helium/air mixtures rising along a smooth, plane and vertical wall. Mean and fluctuating streamwise and cross stream velocities were measured using laser velocimetry. Self-preserving behavior was observed 92-156 source widths from the source, yielding smaller normalized plume widths and larger near-wall mean velocities than observations within the flow development region nearer to the source. Unlike earlier observations of concentration fluctuation intensities, which are unusually large due to effects of streamwise buoyant instabilities, velocity fluctuation intensities were comparable to values observed in nonbuoyant turbulent wall jets. The entrainment properties of the present flows approximated self-preserving behavior in spite of continued development of the wall boundary layer. Measurements of temporal power spectra and temporal and spatial integral scales of velocity fluctuations are also reported.

Nomenclature

b	=	source width
B_o	=	source buoyancy flux
d	=	source diameter
E_o	=	entrainment constant, Eq. (11)

Keywords: Natural Convection, Nonintrusive Diagnostics, Plumes, Turbulence

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$E_u(n), E_v(n)$ = temporal power spectral densities of u and v
f = mixture fraction
$F(y/(x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{f}$
$F'(y/(x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{f}'$
Fr_o = source Froude number, Eq. (2)
g = acceleration of gravity
ℓ_f = characteristic plume width based on $\bar{f}$, Eq. (7)
ℓ_M = Morton length scale, Eq. (1)
ℓ_u = characteristic plume width based on $\bar{u}$, Eq. (7)
n = frequency
PDF(f) = probability density function of mixture fraction
Q = plume volumetric flow rate per unit length
Re_c = characteristic plume Reynolds number, Eq. (9)
Re_o = source Reynolds number, $2\bar{u}_o b/\nu_o$
u = streamwise velocity
$U(y/(x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{u}$
$U'(y/((x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{u}'$
$V(y/((x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{v}$
$V'(y/((x-x_o))$ = normalized self-preserving cross stream distribution of $\bar{v}'$
v = cross stream velocity
x = streamwise distance
y = cross stream distance
z = distance along source from its midplane location
Z = source length
Λ_f = spatial integral scale of mixture fraction fluctuations
Λ_u = spatial integral scale of streamwise velocity fluctuations
ν = kinematic viscosity
ρ = density
τ_f = temporal integral scale of mixture fraction fluctuations
τ_u = temporal integral scale of streamwise velocity fluctuations

Subscripts

max = condition where the property reaches a maximum value

o	=	initial value or virtual origin location
∞	=	ambient value

Superscripts

$\overline{(\ )}$	=	time-averaged mean value
$\overline{(\ )}'$	=	root-mean-squared fluctuating value

Introduction

Plane turbulent wall plumes are caused by line sources of buoyancy along the base of flat walls. These flows are of interest because they are a classical buoyant turbulent flow having numerous practical applications for mixing during confined natural convection processes and in unwanted fires. These flows are also useful for gaining a better understanding of buoyancy/turbulence interactions, and the role of surfaces for inhibiting the large-scale motion mainly responsible for turbulent mixing, as part of developing methods of predicting the properties of buoyant turbulent flows. Motivated by these observations, the objective of the present investigation was to extend recent measurements of mixing processes (mixture fraction or composition statistics) in plane turbulent wall plumes along vertical surfaces, due to Sangras et al. (1999), to consider the velocity statistics of these flows. Present observations were limited to turbulent wall plumes along smooth plane vertical surfaces for conditions where the streamwise buoyancy flux is conserved, which corresponds to flow along an adiabatic wall for a thermal plume.

Present measurements emphasize fully-developed conditions far from the source where effects of source disturbances and momentum have been lost. Free line plumes become self-preserving at these conditions which simplifies reporting and interpreting measurements (Sangras et al., 1998; Tennekes and Lumley, 1972). Adiabatic wall plumes never formally approach self-preserving behavior, however, because the streamwise growth rates of the near-wall boundary layer and the outer plume-like region are not the same. Nevertheless, the outer plume-like region grows more rapidly than the near-wall boundary layer and eventually dominates wall plumes far from the source, where wall plumes approximate self-preserving behavior with scaling similar to free line plumes (Grella and Faeth, 1975; Liburdy and Faeth, 1978; Sangras et al., 1999). Thus, self-preserving behavior of adiabatic wall plumes was sought in this approximate sense during the present investigation.

Early studies of turbulent plumes have been reviewed by Ellison and Turner (1959), Lee and Emmons (1961), List (1982), Papanicolaou and List (1989), Tennekes and Lumley (1972) and Turner (1973). An interesting feature of the early studies is that the entrainment rates observed for wall plumes were much smaller than those observed for free line plumes; this behavior was attributed to both the wall preventing mixing on one side and inhibition of the large-scale cross stream turbulent motion needed for effective mixing.

Grella and Faeth (1975) report hot-wire probe measurements of temperatures and streamwise velocities within adiabatic wall plumes using a linear array of small flames as a thermal source of buoyancy. Self-preserving behavior was sought but was not achieved due to the limited dynamic range of hot wire probes while buoyancy fluxes are difficult to define accurately for this study due to near-source heat losses. Ljubaja and Rodi (1981) subsequently predicted the properties of these flows using a turbulence model that allowed for buoyancy/turbulence interactions, finding good agreement far from the source where approximate self-preserving behavior was approached.

Lai et al. (1986) and Lai and Faeth (1987) carried out laser-induced fluorescence (LIF) and laser velocimetry (LV) measurements of mean and fluctuating concentrations and velocities in adiabatic wall plumes. Gas mixtures leaving a slot provided well defined source dimensions and buoyancy fluxes. The observations were used to evaluate predictions based on simplified mixing length and higher-order turbulence models, finding good predictions for mean properties but relatively poor predictions for turbulence properties. These measurements were limited to near-source conditions in order to highlight effects of flow development; therefore self-preserving behavior was not achieved.

Sangras et al. (1999) reconsidered the mixing properties (mixture fraction statistics) of adiabatic wall plumes during the initial phases of the present investigation. LIF was used to measure mean and fluctuating mixture fractions, emphasizing results for self-preserving conditions. In addition to large values of $(x-x_o)/b$ needed to avoid effects of source disturbances, approximate self-preserving behavior also requires large values of $(x-x_o)/\ell_M$ to avoid effects of source momentum, where ℓ_M is the Morton length scale (Turner, 1973). Noting that plume behavior dominates adiabatic wall plumes at self-preserving conditions, ℓ_M can be defined by analogy to free line plumes having uniform source properties, as follows (List, 1982):

$$\ell_M/b = (\rho_o/\rho_\infty)\, u_o^2/(b u_o g\, |\rho_o-\rho_\infty|/\rho_\infty)^{2/3} \qquad (1)$$

Sangras et al. (1999) found that self-preserving behavior was observed farther from the source than distances considered in earlier work, e.g., $(x-x_o)/b > 92$ and $(x-x_o)/\ \ell_M > 12$, and yielded smaller normalized plume widths and near-wall mean mixture fractions than previously thought. This finding provides strong motivation to find the velocity statistics of adiabatic wall plumes at similar conditions.

In view of these observations, the objective of the present investigation was to measure the mean and fluctuating velocity properties of adiabatic wall plumes, emphasizing conditions within the approximate self-preserving region far from the source. The experiments were similar to Sangras et al. (1999) and consisted of helium/air source flows, along a smooth plane and vertical wall in still air at standard temperature and pressure, which provides straightforward specifications of source dimensions and plume buoyancy fluxes. Measurements of mean and fluctuating velocities were carried out using laser velocimetry.

Experimental Methods

Apparatus. The test apparatus was the same as the earlier free line plume study of Sangras et al. (1998), except for provision of a vertical wall as discussed by Sangras et al. (1999). The plumes were observed in an enclosure (3400 × 2000 × 3600 mm high) that had porous side walls (parallel to the source) and a porous ceiling made of filter material. This approach controlled room disturbances and ambient light leakage into the test enclosure while allowing free inflow of entrained air and free exhaust of the plume. The source slot (876 mm long × 9.4 mm wide) was mounted flush to a flat floor (876 mm long × 610 mm wide) with the vertical wall mounted adjacent to one edge of the slot. The floor/slot/wall assembly was mounted in turn normal to end walls (2440 mm high × 610 mm wide). A screen array (2 screens, 16 mesh × 0.20 mm wire diameter, separated by a distance of 38 mm) was installed across the outer edge of the end walls (facing the vertical wall) to further control room disturbances, following Gutmark and Wygnanski (1976), Sangras et al. (1999) and references cited therein. The entire floor/slot/wall assembly was traversed to accommodate rigid optical instruments in the same manner as Sangras et al. (1999).

Gas supplies to the source were metered and measured using critical flow orifices in conjunction with pressure regulators. These flow rates were calibrated using either wet test or turbine flow meters. After mixing, the source flows passed through beds of iodine flakes and feed lines having length-to-diameter ratios of 1200 to ensure uniformly seeded mixtures. Uniform source flow properties were provided by a bed of beads, a filter and a 3.4:1 contraction at the slot exit.

Instrumentation. Dual-beam frequency-shifted LV was used for velocity measurements, based on the 514.5 nm of an argon-ion laser. The optical axis of the LV passed horizontally through the flow with off-axis signal collection to yield a measuring volume having a diameter of 400 μm and a length of 260 μm. Vertical and horizontal orientations of the plane of the laser beams were used to find the streamwise and cross stream velocity components, similar to Lai and Faeth (1987).

The detector output was amplified and processed using a burst counter signal processor (TSI, model 1980B). Similar to past work, the low-pass filtered analog output of the signal processor was sampled at equal time intervals in order to avoid problems of velocity bias (Dai et al., 1995a,b), while directional ambiguity and bias were controlled by frequency shifting. The detector output was sampled at rates more than twice the break frequency of the low-pass filter in order to control alias signals. Only the ambient flow was seeded because mixture fractions are small in the self-preserving region so that effects of concentration bias when seeded in this way are negligible. Seeding levels were sufficiently large that effects of step noise did not have a significant effect on determinations of rms velocity fluctuations (Adrian and Yao, 1987); this will be quantified later based on measurements of temporal power spectral densities. Experimental uncertainties were estimated similar to past work (Sangras et al., 1998,1999); they were mainly governed by finite sampling time limitations and are estimated to be less than 5 percent for mean streamwise velocities, less than 13 percent for rms velocity fluctuations and less than 20 percent for mean cross stream velocities (the last being relatively large due to the small magnitudes of this velocity component).

Test Conditions. The test conditions were the same as the earlier adiabatic wall plume study of Sangras et al. (1999) and are summarized in Table 1. Two source flows were considered in order to test scaling of source properties in the region of self-preserving behavior. Approximate self-preserving behavior for adiabatic wall plumes was only observed relatively far from the source where $(x-x_o)/b \geq 92$ and $(x-x_o)/\ell_M \geq 12$; therefore, the locations of the virtual origin could not be distinguished from $x_o/b = 0$ within present experimental uncertainties. Finally, the source Froude numbers, Fr, defined for adiabatic wall plumes by analogy to free line plumes, as follows:

$$Fr^2 = \rho_o u_o^2/(2bg|\rho_\infty-\rho_o|) \qquad (2)$$

were selected to approximate Froude numbers far from the source in order to enhance the development of the flow toward self-preserving behavior, following George et al. (1977).

Self-Preserving Scaling

The state relationship for density as a function of mixture fraction, assuming an ideal gas mixture far from the source where the flow becomes self-preserving, is as follows (Dai et al., 1994):

$$\rho = \rho_\infty + f\rho_\infty (1 - \rho_\infty/\rho_o), \; f << 1 \qquad (3)$$

Assuming approximate self-preserving behavior for adiabatic wall plumes, in the sense discussed earlier, yields the following expressions for mean and fluctuating mixture fractions and velocities (List, 1982):

$$F(y/(x-x_o)) \text{ or } F'(y/(x-x_o)) = (\bar{f} \text{ or } \bar{f}')gB_o^{-2/3}(x-x_o)|1 - \rho_\infty/\rho_o| \qquad (4)$$

$$U(y/(x-x_o) \text{ or } U'(y/(x-x_o) = U(\bar{u} \text{ or } \bar{u}')/B_o^{1/3} \qquad (5)$$

$$V(y/(x-x_o) \text{ or } V'(y/(x-x_o) = (\bar{v} \text{ or } \bar{v}')/B_o^{1/3} \qquad (6)$$

where $F(y/(x-x_o))$, $F'(y/(x-x_o))$, etc., are appropriately scaled cross stream profile functions of mean and fluctuating mixture fractions and velocities, which approximate universal functions far from the source. Characteristic plume widths, ℓ_f and ℓ_u, based on $\bar{f}$ and $\bar{u}$ are also defined, similar to turbulent free line plumes, as follows (Dai et al., 1994):

$$F(\ell_f/(x-x_o))/F(0) = e^{-1}; \; U(\ell_u/(x-x_o))/U_{max} = e^{-1} \qquad (7)$$

For plane turbulent adiabatic wall plumes, F decreases monotonically from its value of F(0) at the wall and there is only one location where Eq. (7) is satisfied. In contrast, U satisfies Eq. (7) at two locations, in the boundary-layer-like region near the wall and in the outer plume-like region; the outer plume-like region is used when applying Eq. (7). The source buoyancy flux, B_o, is a conserved scalar of the flow which can be found as follows for plane plumes having uniform source properties (List, 1982):

$$B_o = bu_o g|\rho_o - \rho_\infty| / \rho_\infty \quad (8)$$

The corresponding characteristic plume Reynolds number can be written as follows for approximate self-preserving conditions (Sangras et al., 1999):

$$Re_c = \bar{u}_{max} \ell_u / \nu_\infty = U_{max} B_o^{1/3} \ell_u / \nu_\infty \quad (9)$$

Values of U_{max} and ℓ_u were available from measurements in the self-preserving region of the flow for the present test conditions; they were obtained from measurements farthest from the source for earlier studies.

Results and Discussion

Mean Velocities. Distributions of mean velocities in the approximate self-preserving region of the flow will be considered first. Present measurements of cross stream distributions of mean streamwise velocities for the two sources are illustrated in Fig. 1. The scaling parameters of Eq. (5) have been used when plotting the figure so that the value of the ordinate is $U(y/(x-x_o))$. Results for $z/Z = 0$ and 1/4 (where z is measured from a position halfway between the end walls), are in good agreement with each other which confirms the two-dimensionality of the flow. A least-squares correlation of present measurements is shown on the following plots to help indicate the trends of the measurements. The present measurements also yield universal distributions within experimental uncertainties for $92 \leq (x-x_o)/b \leq 155$ and $12 \leq (x-x_o)/\ell_M \leq 21$ with flow aspect ratios of $Z/\ell_u \geq 7.9$, as required for self-preserving flow and in agreement with earlier findings for mean mixture fractions due to Sangras et al. (1999). Present conditions within the self-preserving region of the flow correspond to $3800 \leq Re_c \leq 6700$ which is similar to the Reynolds number range considered for self-preserving round and plane turbulent free plumes by Dai et al. (1994,1995a,b,1996) and Sangras et al. (1998). These values are comparable to the largest values of Re_c that have been considered for wakes, which exhibit self-preserving turbulence properties for Re_c as small as 70 (Wu and Faeth, 1993); therefore, present Reynolds numbers are large enough to be representative of fully developed turbulent flows. The adequacy of the present Reynolds number range is also confirmed by present measurements of turbulence spectra to be considered later.

Measurements of U from other studies of turbulent adiabatic wall plumes on vertical surfaces are also plotted in Fig. 1 for comparison with the present measurements, including results from Grella and Faeth (1975) and Lai et al. (1986). The measurements of Grella and Faeth (1975) and Lai et al. (1986) exhibit streamwise variations of U implying that self-preserving behavior was not reached; therefore, their results plotted in Fig. 1 are for conditions farthest from the source.

Considering the three sets of measurements illustrated in Fig. 1, it is evident that the results of Lai et al. (1986) are considerably broader than present results (33 percent broader at the 1/e points of the distributions) and that while the normalized width of the distribution of Grella and Faeth (1975) is comparable to present results, the maximum value of U is somewhat larger. The larger widths of U for the measurements of Lai et al. (1996) are typical of conditions in developing plumes before self-preserving behavior is reached. Flow development affects the results of Lai et al. (1986) which were limited to $(x-x_o)/b \leq 37.5$ whereas self-preserving behavior was only observed much farther from the source $(x-x_o)/b \geq 92$, during the present study. This behavior is illustrated by the values of $\ell_f/(x-x_o)$ summarized in Table 2 for the measurements of Lai et al. (1986) and the present investigation; the progressive reduction of $\ell_u/(x-x_o)$ with increasing distance from the source, tending toward values observed in the present investigation, is quite evident. Similar trends were observed with respect to F for adiabatic wall plumes by Sangras et al.

(1999). Distances from the source cannot be quantified for the measurements of Grella and Faeth (1975) because an array of small flames was used for the source but consideration of flow widths suggest that their results farthest from the source are approaching self-preserving behavior. As pointed out by Sangras et al. (1999), however, the results of Grella and Faeth (1975) are still problematical because these evaluations of B_o were based on mean mixture fraction and streamwise velocity distributions which ignores the appreciable streamwise turbulent flux of B_o in the present plumes (found to be 28 percent of the total). This causes values of U from Grella and Faeth (1975) to be somewhat overestimated (by roughly 9 percent based on present measurements of the streamwise turbulent flux of mixture fraction) in agreement with the observations of Fig. 1.

The test conditions and results of various existing velocity measurements of wall plumes and free line plumes are summarized in Table 3. Studies considered include the adiabatic wall plume measurements of Grella and Faeth (1975), Lai et al. (1986) and the present investigation, the isothermal wall plume measurements of Liburdy and coworkers (1978, 1979), and the free line plume measurements of Rouse et al. (1952) and Ramaprian and Chandrasekara (1989). Parameters are given in the table to the extent that they are known for each study, as follows: the aspect ratio of the source, Z/b, the range of streamwise distances, $(x-x_o)/b$, the smallest flow aspect ratio, $(Z/\ell_u)_{min}$, the range of streamwise distances in terms of Morton length scale, $(x-x_o)/\ell_M$, the characteristic flow width, $\ell_u/(x-x_o)$, the maximum normalized streamwise velocity, U_{max}, the entrainment coefficient, E_o, and the maximum streamwise and cross stream velocity fluctuations, $\bar{u}'_{max}/\bar{u}_{max}$ and $\bar{v}'_{max}/\bar{u}_{max}$. The earlier measurements of Grella and Faeth (1975), Lai et al. (1986) and Ramaprian and Chandrasekara (1989) continue to vary with increasing distance from the source so that only results farthest from the source are tabulated. The measurements of Rouse et al. (1951), Grella and Faeth (1975) and Liburdy and coworkers (1978,1979) employed linear arrays of flames as thermal sources for plumes so that source dimensions cannot be prescribed for these studies. The behavior of mean streamwise velocities for the various wall plumes is similar and has already been discussed in connection with Fig. 1. Earlier measurements of mixture fraction statistics in free-line plumes due to Sangras et al. (1998) show that the measurements of Rouse et al. (1952) and Ramaprian and Chandrasekara (1989) did not reach self-preserving behavior; nevertheless, it is still interesting to compare these results with present findings for adiabatic wall plumes. In particular, the characteristic plume widths, ℓ_u, are up to 2.1 times larger and scaled values of U_{max} up to 37 percent smaller for free line plumes than for the present adiabatic wall plumes. These differences come about because the free line plumes mix on both sides while the wall plumes can only mix on one side (note that B_o refers to the buoyancy flux of the entire flow in both cases) with additional reduced mixing for the wall plumes because the wall inhibits the large scale turbulent motions that are mainly responsible for mixing. These effects have unfortunate implications for unwanted fires because reduced mixing rates allow heated regions to extend farther from the source than would be the case for unconfined plumes (Sangras et al., 1999).

Present measurements of cross stream distributions of cross stream mean velocities for the two sources are illustrated in Fig. 2. The scaling parameters used for the figure provide universal plots in the self-preserving region as well as a check of the internal consistency of the present measurements of $\bar{u}$ and $\bar{v}$. Carrying out this evaluation as described by Dai et al. (1995a), based on the present streamwise velocity measurements illustrated in Fig. 1, yields the prediction calculated from the continuity equation illustrated in Fig. 2. The measurements illustrated in Fig. 2 exhibit universal behavior for the various test conditions, as anticipated for the self-preserving region. Additionally, the measurements of $\bar{v}$ also are consistent with the present measurements of $\bar{u}$ through the continuity equation.

The asymptotic values of $\bar{v}$ at large values of $y/(x-x_o)$ are proportional to the entrainment constant of the plumes, which is important for integral theories of plume scaling and as a measure of turbulent mixing rates (Ellison and Turner, 1959; Turner, 1973). Entrainment behavior can be seen by integrating the continuity equation in the cross stream direction to obtain an expression for the rate of change of the volumetric flow rate within the plume, per unit plume length, at self-preserving conditions where the density of the flow is nearly constant, as follows:

$$d/dx \int_0^\infty \bar{u}\,dy = dQ/dx = -\bar{v}_\infty \qquad (10)$$

Then defining the entrainment constant based on $\bar{u}_{max}$, there results

$$E_o = -\bar{v}_\infty/\bar{u}_{max} \qquad (11)$$

which provides the result summarized in Table 3. Notably, measured entrainment constants for the three adiabatic wall plume studies are in excellent agreement in spite of potential effects of flow development (problems of finding B_o accurately are not a factor here because this parameter does not appear in Eq. (11)). Values of E_o, however, are only roughly half as large for wall plumes than for free line plumes which is consistent with effects of the wall inhibiting turbulent mixing as mentioned earlier (with potential effects of flow development for the free-line plumes being a contributing factor)

Velocity Fluctuations. Measurements of cross stream distributions of streamwise and cross stream velocity fluctuations are illustrated in Fig. 3. In addition to the present measurements for the same conditions as the measurements of U in Fig. 1, other measurements for adiabatic wall plumes have been plotted from Grella and Faeth (1975), Lai et al. (1986) and Lai and Faeth (1987). As before, the earlier measurements do not extend to fully self-preserving conditions so that only their results farthest from the source are shown. The scaling used for the variables in Fig. 3 is the same as Figs. 1 and 2 and corresponds to the self-preserving variables, U´ and V´, of Eqs. (5) and (6).

Present measurements of U´ and V´ in Fig. 3 exhibit self-preserving behavior within experimental uncertainties over the test range. Values of U´ and V´ become small as the wall and the free stream are approached and reach a maximum near $y/(x-x_o) \approx 0.05$, which is in the region of the maximum mean streamwise velocity gradient (see Fig. 1) where turbulence production is a maximum. Maximum velocity fluctuations in adiabatic wall plumes and free-line plumes, and the value of anisotropy based on maximum velocity fluctuatins of 3/2, are similar, see Table 3. In contrast, the effect of the wall on stabilizing mixing is more apparent for mixture fraction fluctuation intensities where maximum values are larger, 47 percent, for free-line plumes than for adiabatic wall plumes, 37 percent. Finally, present values of velocity fluctuations generally are larger than the earlier measurements of Grella and Faeth (1975), Lai and Faeth (1987) and Lai et al. (1986); this can be attributed to effects of flow development with problems of using hot wires in strongly turbulent flows serving as a contributing factor for the measurements of Grella and Faeth (1975).

Temporal Power Spectral Densities. Typical temporal power spectra of streamwise and cross stream velocity fluctuations are illustrated in Figs. 4 and 5 for self-preserving turbulent adiabatic wall plumes. These results for various cross stream positions, $y/(x-x_o) = 0.02$-0.08, for $(x-x_o)/b = 110$ and 156 for the case 1 plume but results for other self-preserving conditions are similar. The measurement of streamwise spectra are normalized by local turbulence properties as described by Hinze (1975); the measurements of cross stream spectra are normalized using the same parameters. The spectra are relatively independent of both radial and streamwise position when normalized in the manner of Figs. 4 and 5. The spectra decay according to the $-5/3$ power of frequency, analogous to the well-known inertial-convective region for scalar property and velocity fluctuations in nonbuoyant turbulence (Tennekes and Lumley, 1972), for the range of frequencies that could be considered during the present investigation. Usually, a decay according to the -3 power of frequency, analogous to the inertial-diffusive region seen for turbulence in buoyant flows, is observed at larger frequencies, see Sangras et al. (1999). Unfortunately, this region could not be observed during the present investigation due to dynamic range limitations of the LV measurements. In spite of this limitation, however, it is evident that present spectra are noise-free for several decades implying reasonably accurate determinations of velocity fluctuations. An apparent exception is the scattering of the spectra for cross stream velocity fluctuations at small frequencies seen in Fig. 5. This apparent scattering comes about due to a dip in the spectra of cross stream velocity fluctuations at small frequencies, see Hinze (1975), which tends to look like noise when results for various positions in the flows are illustrated because the dip does not begin at exactly the same normalized frequency at all positions in the self-preserving region of the plumes.

Integral Scales. Measured values of temporal integral scales based on streamwise velocity fluctuations for the present self-preserving turbulent adiabatic wall plumes are illustrated in Fig. 6. Earlier measurements of temporal integral scales based on mixture fraction fluctuations, due to Sangras et al. (1999), are also shown on the plot for comparison with the present measurements. Additionally, spatial integral scales were found from the temporal integral scale data using Taylor's hypothesis, e.g.

$$\Lambda_u = \bar{u}\tau_u, \quad \Lambda_f = \bar{u}\tau_f \qquad (12)$$

and are also illustrated in Fig. 6. Self-preserving normalization has been used for all the integral scales, similar to earlier treatments of integral scales for round buoyant turbulent plumes (Dai et al., 1994,1995a,b). All the integral scales approximate universal behavior for self-preserving conditions when plotted in the manner of Fig. 6. Spatial integral scales progressively decrease as the cross stream distance increases, which is expected considering the topography of the turbulence-containing region of the flow. The corresponding increase of temporal integral scales near the edge of the flow is caused by smaller mean velocities in this region through Taylor's hypothesis.

Conclusions

Velocity statistics were measured in turbulent adiabatic wall plumes rising along plane smooth vertical walls in still air. Conditions far from the source were emphasized where effects of source disturbances are lost and the outer plume-like region of the flow approximates self-preserving behavior with scaling similar to self-preserving free line plumes. The test conditions consisted of buoyant jet sources of helium and air to obtain the source properties summarized in Table 1 with measurements involving $(x-x_o)/b$ in the range 92-155 and $(x-x_o)/\ell_M$ in the range 12-21. The major conclusions of the study are as follows:

1. The present measurements yielded distributions of mean streamwise velocities in self-preserving plumes that were up to 22 percent narrower, with maximum scaled values up to 75 percent different, than earlier measurements in the literature. There were two main reasons for these differences: the results of Lai et al. (1986) were limited to $(x-x_o)/b \leq 38$, which is not a sufficient distance from the source to observe self-preserving behavior in spite of effects to promote rapid streamwise development of the flow; and in the case of Grella and Faeth (1975), estimations of buoyancy fluxes based on measured profiles of mean mixture fractions and velocities introduce significant experimental uncertainties and overestimate normalized streamwise velocities because the relatively large streamwise turbulent flux of B_o (comprising 28 percent of the total based on present measurements) is ignored.

2. Cross stream distributions of velocity fluctuations are anisotropic near the maximum velocity condition ($\bar{u}'/\bar{v}' \approx 1.5$) with a tendency to become more isotropic near the edge of the flow. Maximum intensities of streamwise velocity fluctuations, 26 percent, are comparable to observations in round free plumes (Dai et al., 1995a) but are significantly smaller than maximum intensities of mixture fraction fluctuations, 47 percent, which are enhanced due to buoyancy/turbulence interactions. Present normalized values of velocity fluctuations are also roughly 30 percent larger than earlier observations of Lai et al. (1986) and Grella and Faeth

(1975) due to problems of flow development and buoyancy flux determinations for these earlier studies that were mentioned earlier.

3. Present measurements of velocity statistics support earlier findings based on mixture fraction statistics that the self-preserving plane turbulent adiabatic wall plumes mix much slower than comparable free line plumes. In particular, characteristic plume widths are up to 100 percent larger and scaled maximum mean streamwise velocities are up to 40 percent smaller for free line plumes than for the present adiabatic wall plumes. These differences come about because the wall limits mixing to one side of the flow and inhibits the large-scale motion that is mainly responsible for turbulent mixing.

4. Temporal power spectra of velocity fluctuations scale in a relatively universal manner. The spectra exhibit the well known –5/3 power inertial-convective decay region but present measurements did not extend to sufficiently large frequencies to resolve the –3 power inertial-diffusive decay region that is generally observed in buoyant turbulent flows.

5. Temporal and integral scales could be correlated in a relatively universal manner in terms of self-preserving parameters. Temporal integral scales were smallest near the maximum streamwise velocity condition which follows from Taylor's hypothesis in view of the relatively slow variation of integral length scales in this region.

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Table 1. Summary of plane buoyant turbulent adiabatic wall plume test conditions[a]

Source Properties	Case 1	Case 2
Helium concentration (percent by volume)	29.0	52.3
Density (kg/m^3)	0.871	0.639
Kinematic viscosity (mm^2/s)	22.1	31.3
Average velocity (mm/s)	868	1240
Buoyancy flux, $B_o(m^3/s^3)$	0.0200	0.0514
Density ratio, ρ_o/ρ_∞	0.750	0.550
Reynolds number, Re_o	740	745
Froude number, Fr_o	3.50	3.20
Morton length scale, ℓ_M/b	7.7	6.1

[a]Helium/air sources directed vertically upward at the base of a vertical smooth plane wall in still air with an ambient pressure of 99 ± 0.5 kPa and temperature of 297 ± 0.5 K. Pure gas properties as follows: air density of 1.161 kg/m^3, air kinematic viscosity of 15.9 mm^2/s, helium density of 0.163 kg/m^3 and helium kinematic viscosity of 122.5 mm^2/s. Source slot width and length of 9.4 and 876 mm. Virtual origin based on $\bar{f}$ of $x_o/b = 0$ determined from present measurements in the range $(x-x_o)/b$ =92-155 and $(x-x_o)/\ell_M$ = 12-21.

Table 2. Development of plane turbulent adiabatic wall plumes[a]

Source	Condition	$(x-x_o)/b$	$\ell_u/(x-x_o)$
Lai et al. (1986)	Developing	10.0	0.183
		20.0	0.133
		37.5	0.108
Present	Self-preserving	92-156	0.081

[a]Plane turbulent adiabatic wall plumes along smooth vertical surfaces in still and unstratified environments.

Table 3. Summary of self-preserving velocity properties of plane buoyant turbulent plumes[a]

Source	Present Study	Lai et al. (1986)[b]	Grella & Faeth (1975)[b,c]	Liburdy & coworkers (1978,1979[b],[c])	Ramaprian & Chandrasekhara (1989)[d]	Rouse et al. (1952)[b,c]
Plume Type	Adiabatic Wall	Adiabatic Wall	Adiabatic Wall	Isothermal Wall	Free-line	Free-line
Z/b	93	38	---	---	50	---
$(x-x_o)/b$	92-156	10-38	---	---	25-65	---
$(Z/\ell_u)_{min}$	7.9	10.8	13.0	5.9	2.6[d]	---
$(x-x_o)/\ell_M$	12-21	1-5	---	---	3-15	---
$\ell_u/(x-x_o)$	0.081	0.117	0.080	0.124	0.126	0.177
U_{max}	2.84	2.14	3.16	2.90	2.10	1.80
E_o	0.068	0.071	0.067	0.096	0.11	0.14
$\bar{u}'_{max}/\bar{u}_{max}$	0.26	0.25	0.16	0.20	0.27	---
$\bar{v}'_{max}/\bar{u}_{max}$	0.17	0.18	---	0.11	0.20	---

[a]Plane buoyant turbulent plumes in still and unstratified environments. Range of streamwise distances are for conditions where quoted self-preserving properties were found from measurements over the cross section of the plumes. Entries are ordered chronologically.
[b]These flows were evolving over the range of the measurements and results shown pertain to distances farthest from the source.
[c]Source was a linear array of round jets so that slot properties cannot be specified.
[d]This value is $(Z/(2\ell_u))_{min}$ which is the full width of the flow, similar to wall plume entries.

List of Figures

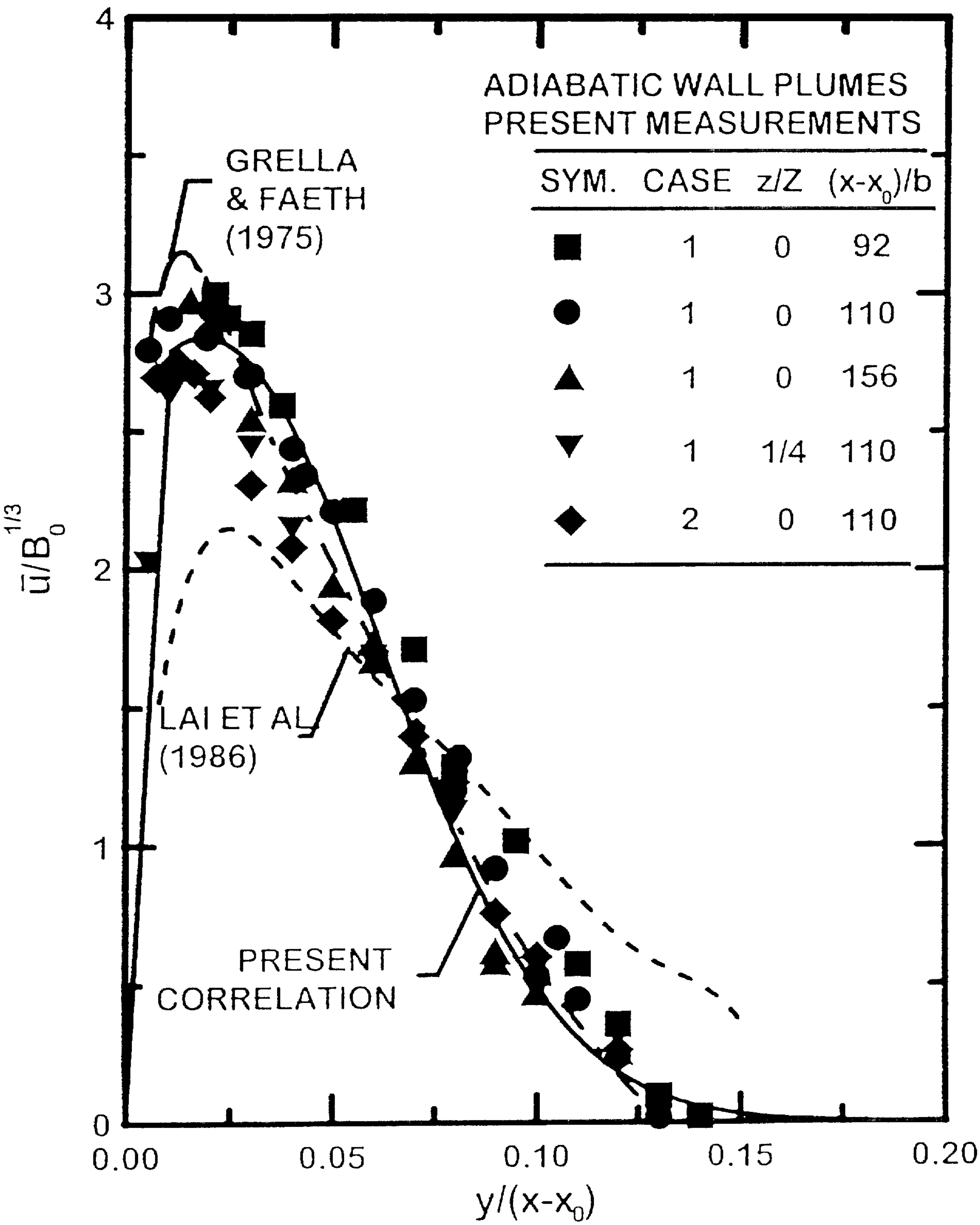
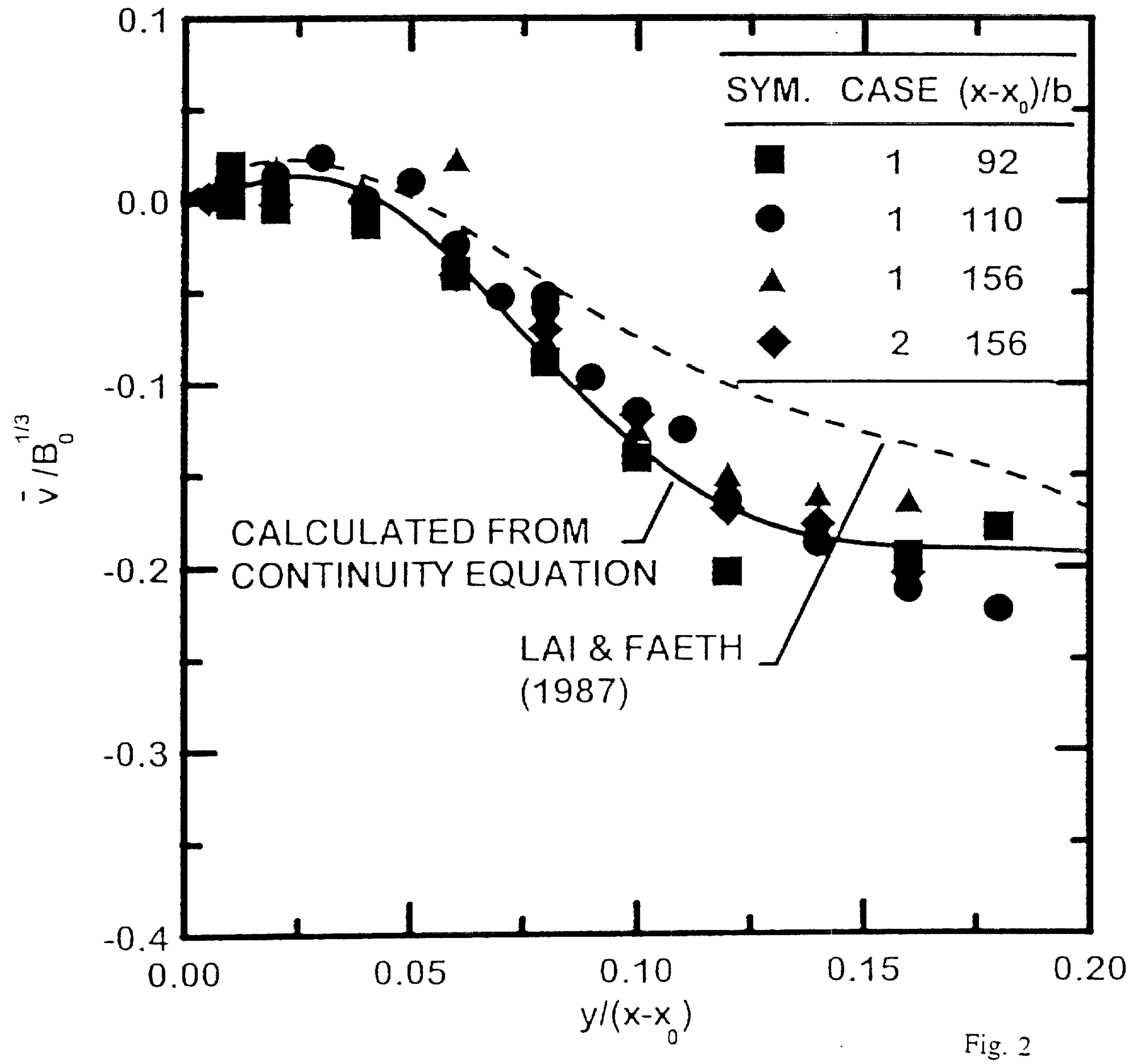

ADIABATIC WALL PLUMES
PRESENT MEASUREMENTS
SYM. CASE z/Z $(x-x_0)/b$
1 0 92
1 0 110
1 0 156
1 1/4 110
2 0 110
GRELLA & FAETH (1975)
LAI ET AL (1986)
PRESENT CORRELATION
$\bar{u}/B_0^{1/3}$
$y/(x-x_0)$
0 1 2 3 4
0.00 0.05 0.10 0.15 0.20

Fig. 1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0.0
-0.1
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-0.3
-0.4
0.00
0.05
0.10
0.15
0.20
$\bar{v}/B_0^{1/3}$
$y/(x-x_0)$
SYM. CASE $(x-x_0)/b$
1 92
1 110
1 156
2 156
CALCULATED FROM
CONTINUITY EQUATION
LAI & FAETH
(1987)

Fig. 2

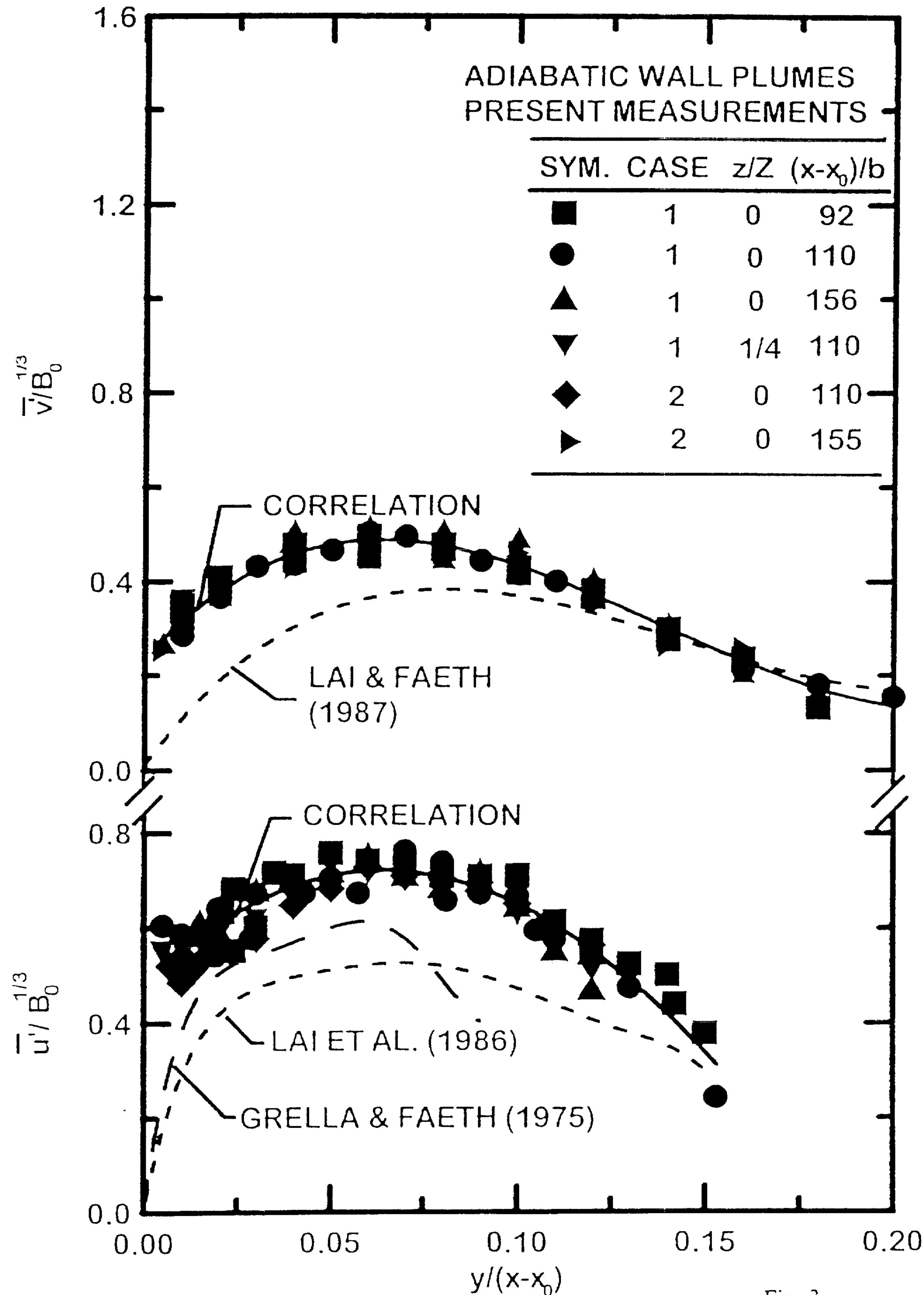
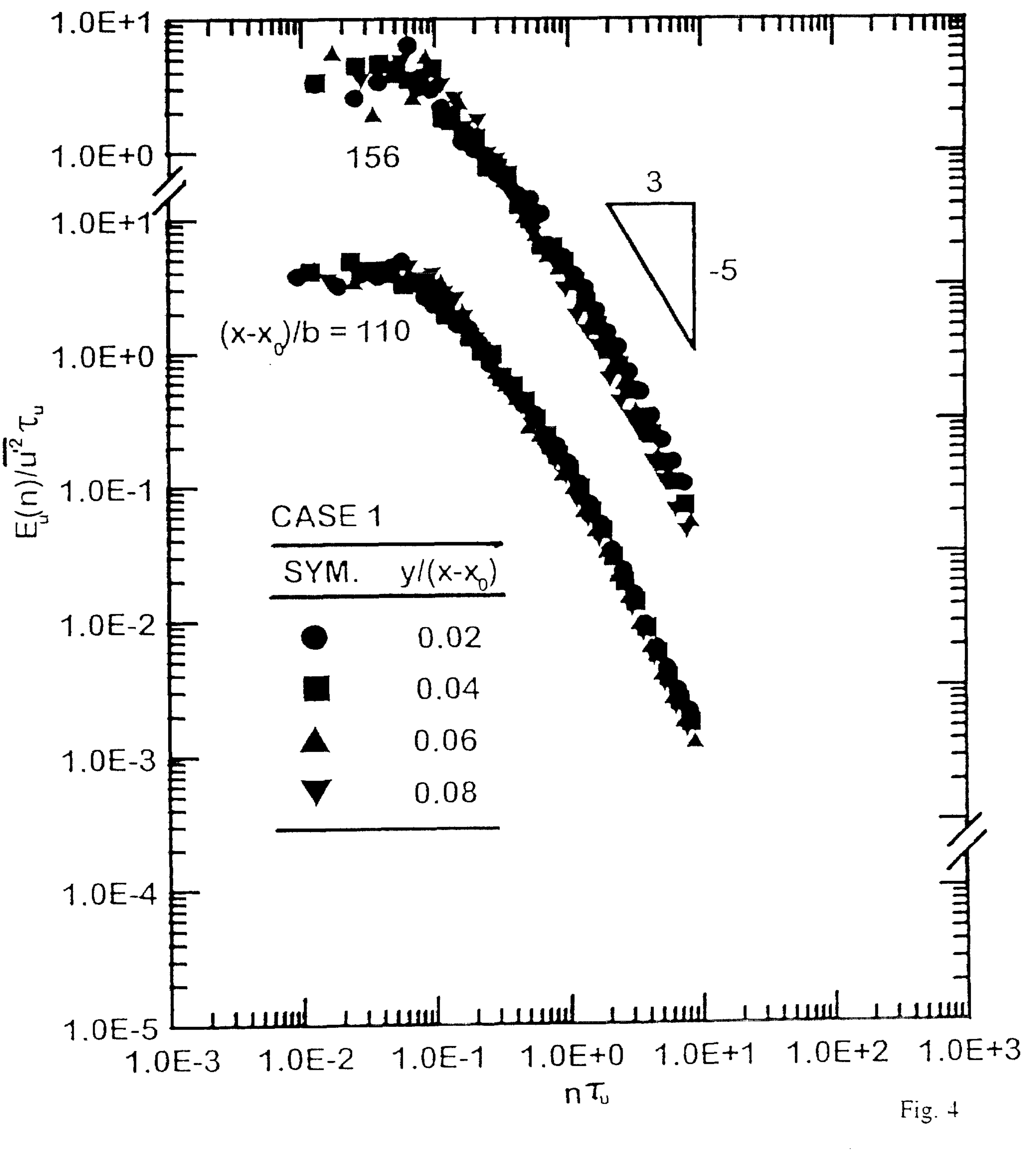

ADIABATIC WALL PLUMES
PRESENT MEASUREMENTS
SYM. CASE z/Z (x-x0)/b
1 0 92
1 0 110
1 0 156
1 1/4 110
2 0 110
2 0 155
CORRELATION
LAI & FAETH (1987)
CORRELATION
LAI ET AL. (1986)
GRELLA & FAETH (1975)
v'/B0^1/3
u'/B0^1/3
y/(x-x0)
0.0
0.4
0.8
1.2
1.6
0.00
0.05
0.10
0.15
0.20

Fig. 3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1.0E+0
1.0E+1
1.0E+0
1.0E-1
1.0E-2
1.0E-3
1.0E-4
1.0E-5
156
3
-5
(x-x0)/b = 110
E_u(n)/u'^2 τ_u
CASE 1
SYM. y/(x-x0)
0.02
0.04
0.06
0.08
1.0E-3
1.0E-2
1.0E-1
1.0E+0
1.0E+1
1.0E+2
1.0E+3
n τ_u

Fig. 4

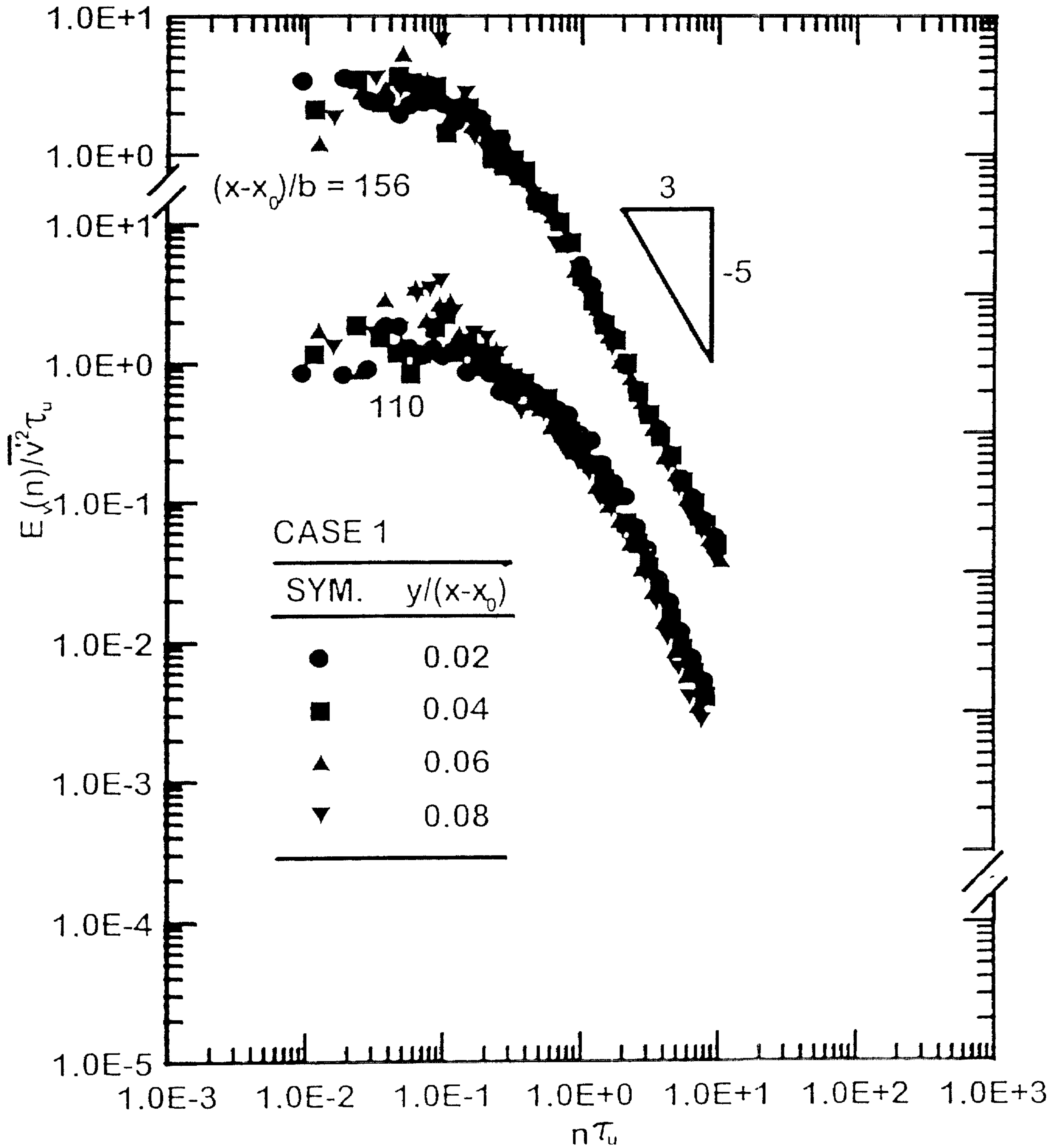
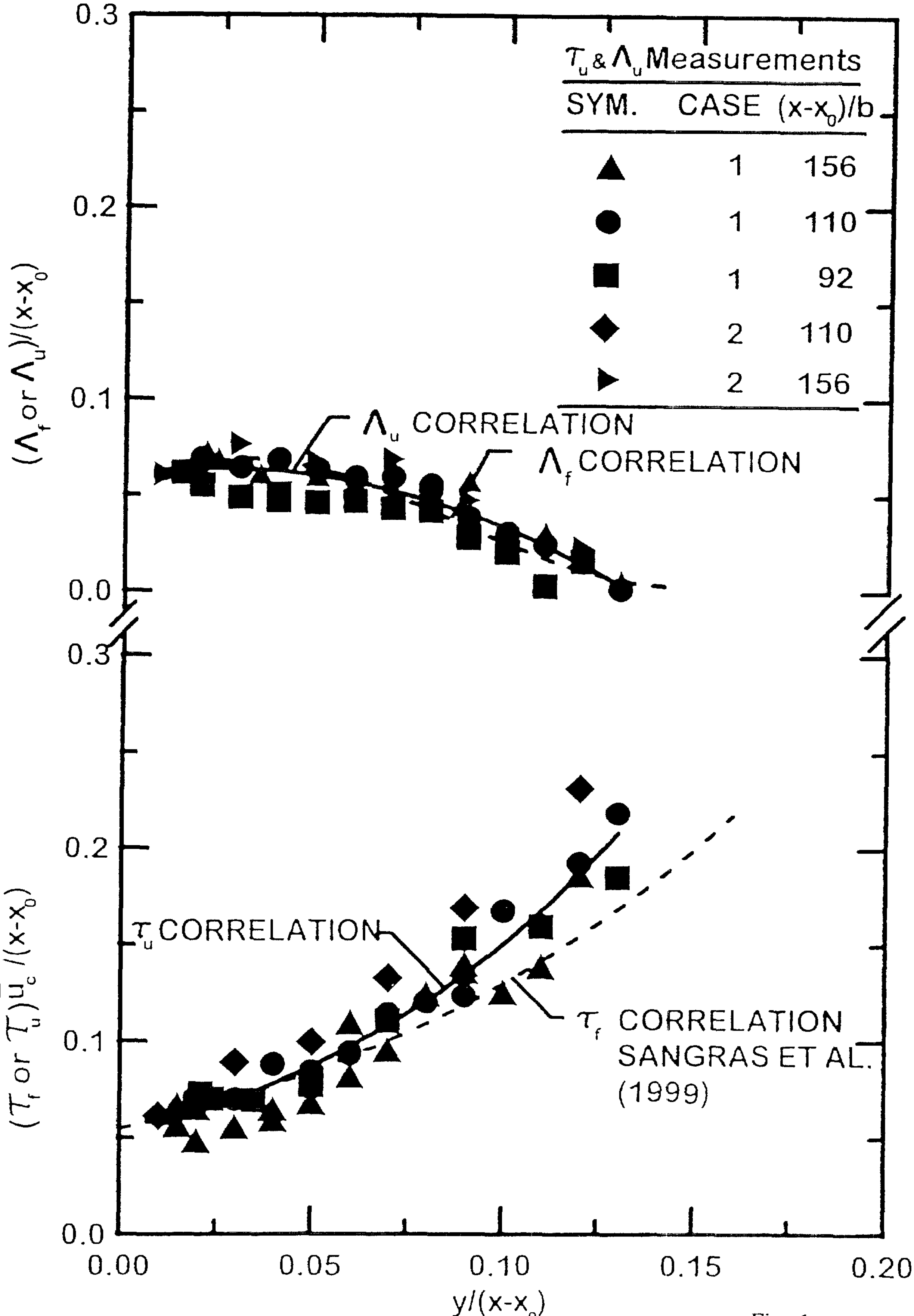

1.0E+1
1.0E+0
(x-x$_0$)/b = 156
1.0E+1
1.0E+0
110
1.0E-1
1.0E-2
1.0E-3
1.0E-4
1.0E-5
3
-5
CASE 1
SYM. y/(x-x$_0$)
0.02
0.04
0.06
0.08
1.0E-3 1.0E-2 1.0E-1 1.0E+0 1.0E+1 1.0E+2 1.0E+3
$n\tau_u$
$E_v(n)/\overline{v'^2}\tau_u$

Fig. 5



τ_u & Λ_u Measurements
SYM. CASE $(x-x_0)/b$
1 156
1 110
1 92
2 110
2 156
Λ_u CORRELATION
Λ_f CORRELATION
τ_u CORRELATION
τ_f CORRELATION SANGRAS ET AL. (1999)
$(\Lambda_f$ or $\Lambda_u)/(x-x_0)$
$(\tau_f$ or $\tau_u)\bar{u}_c/(x-x_0)$
$y/(x-x_0)$
0.0
0.1
0.2
0.3
0.00
0.05
0.10
0.15
0.20

Fig. 6