Velocity and Scalar Fields of Turbulent Premixed Flame in Stagnation Flow

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Abstract

Detailed experimental measurements of the scalar and velocity statistics of premixed methane/air flames stabilized by a stagnation plate are reported. Conditioned and unconditioned velocity of two components and the reaction progress variable are measured by using a two-component laser Doppler velocimetry technique and Mie scattering technique, respectively. Experimental conditions cover equivalence ratios of 0.9 and 1.0, incident turbulence intensities of 0.3 to 0.45 m/s, and global stretch rates of 100 to 150 sec^{-1}. The experimental results are analyzed in the context of the Bray-Moss-Libby flamelet model of these flames. The results indicate that there is no turbulence production within the turbulent flame brush and the second and third order turbulent transport terms are reduced to functions of the difference between the conditioned mean velocity. The result of normalization of these relative velocities by the respective velocity increase across laminar flames suggest that the mean unconditioned velocity profiles are self-similar.

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Introduction

In a recent paper[1] we introduced the use of the turbulent stagnation flow configuration for fundamental studies of premixed turbulent flames. The turbulent flame propagates in the divergent stagnation flow region of a turbulent fuel/air jet impinging on a plate. Depending on flow and mixture conditions the flame brush is stabilized at various distances away from the plate surface where the mean velocity balances the turbulent flame speed. Consequently, flame stabilization is achieved without involving flow recirculation as in the conventional v-flame and conical flame configurations. Moreover, at the centerline, the turbulent flame brush is planar and locally normal to the approach flow so that the turbulent flame speed can be deduced unambiguously from the flow velocity entering the reaction zone. Therefore, this configuration provides a convenient and more accurate means to deduce the turbulent flame speed.[1]

The most significant theoretical implication of this configuration, however, is that it is the closest experimental approximation to the idealized one-dimensional infinite planar flame assumed in many theoretical turbulent combustion models.[2,3] Bray, Champion and Libby[4] (BCL) recognize that a theoretical analysis for the infinite planar flame is limited because the idealized situation cannot be produced in the laboratory. As a result, they have relied on a comparison of their theoretical predictions with experimental measurements made in 2D oblique flames. Although these comparisons have been successful in validating many features of the model, it is however difficult to ascertain whether the discrepancies between predictions and measurements are caused by variations of the flame properties not accounted for in the theory, or by the actual deficiencies in the theory. Hence, encouraged in part by our experimental work, they have recently initiated the modeling of

the stagnation flow stabilized flame so that a more direct and compatible comparison can be made between theoretical and experimental studies. Their first analysis[4] is for the case of flames stabilized in two opposed jets and closure is achieved by the use of conventional gradient transport. Subsequent studies[4] will model the turbulent transport using the Bray-Moss-Libby (BML) flamelet concepts which assumes infinite rate chemistry and zero flamelet thickness.[2]

The stagnation flame configuration is also significant for other numerical models of turbulent combustion, such as the joint probability density function (jpdf) method developed by Pope[5,6] and a deterministic model for simulating the interaction of the flamelet with incident turbulence using the vortex dynamics technique.[7] At present, the jpdf model is capable of predicting the turbulent flame speed and other properties similar to those calculated by the BML model. Vortex dynamic simulations of the stagnation flames compute the dynamic movement of the wrinkled flamelet and also predict the conditioned velocity statistics. This configuration is, therefore, important for the further development of fundamental experimental and theoretical turbulent combustion research.

Since very little is known about the behavior of the stagnation flow stabilized flames, it is necessary to improve our understanding of their fundamental properties through detailed experimental measurement of the scalar and velocity statistics. These experimental data will be useful in the development of theoretical models for this configuration. In response to such a need, we report herein results from an investigation of the scalar and velocity statistics which provide further characterization of the flame properties. Measurements were made of the conditioned and unconditioned velocity of two components and the reaction progress variable $\bar{c}$, a non-

dimensionalized scalar. Features of the mean and rms velocity profiles significant to modeling are discussed. In addition, implications for the closure requirements of the third order turbulence transport are also considered.

Experimental methodology

A uniform axisymmetric flow of premixed methane/air flow is provided by a 50 mm diameter nozzle. This jet of reactants is shielded by a co-flow of air with outer diameter of 100 mm. For this study, the stagnation plate is placed at 75 mm above the exit, and the exit flow velocity is held constant at 5.0 m/s. The incident turbulence is generated by placing at 50 mm upstream of the exit a square grid of 1.0 mm elements with 5.0 mm openings or a perforated plate with 3.2 mm diameter circular holes which gives a 40 % blockage ratio. Mixture and flow conditions of the four flames are listed in Table I. The turbulence Reynolds numbers and Damkohler numbers determined at the nozzle exit indicate that these flame fall within the wrinkled laminar flame regime (Table I).

Flow velocities are measured by a four-beam two-color laser Doppler velocimetry (LDV) system which measures the velocity of the two components using a 10 μsec co-validation criterion. Details of the LDV system and the computer controlled data acquisition system can be found in Ref. 1. Seeding for unconditioned velocity measurement is provided by refractory aluminum oxide particles of 0.3 μm introduced into the jet by a cyclone seed generator. Conditioned velocity measurement in the reactant side is made possible by using a silicon oil aerosol as the LDV seed. The technique is based on the principle that the silicon oil droplets evaporate and burn through the flamelets. A blast atomizer is used to generate the aerosol. At each measurement position, 8192 pairs of validated velocity data are recorded. To

deduce the conditioned velocity statistics in the products, a procedure which involves deconvoluting the velocity pdf's as described in Cheng and Shepherd[8] is used.

The silicone oil seeding technique is also used for measuring the conserved scalar, $\bar{c}$, by monitoring the Mie scattering intensity using a photomultiplier and lens assembly. Within the flame brush, the Mie scattering signal resembles a random telegraph signal with sharp transition between the signal levels representing the reactant and product states. By specifying a threshold criterion, the local value of the conserved scalar is determined by evaluating the percentage of the time spent in the products. Using the zero thickness flamelet approximation, the conserved scalar so determined is identical to the normalized density $(\rho-\rho_p)/(\rho_r-\rho_p)$, where ρ is the mean density and subscripts r and p denote reactants and products. The Mie scattering signal can also be analyzed to obtain other time dependent scalar parameters such as the scalar spectra, flame crossing frequency[9] and pdf's of the flame passage times.[10] The turbulent flame brush thickness is obtained from the distance between the two points on the axial scale intersected by the tangent to the c profile at c=0.5.

Results and discussions

As reported in our previous study, typical flow velocities in the flame region are of the same order of magnitude as the turbulent flame speed. These velocities are lower than those of the other axisymmetric or plane-symmetric flame configurations in which the velocity of the flow entering the flame region is about the same as that of the freestream. Therefore, it becomes necessary to determine whether or not the models developed for high Reynolds numbers are still valid for the stagnation flames. The two criteria for the models are that Re_l, the turbulent Reynolds number based on the integral

length scale and velocity fluctuations, and Da, the large eddy Damkohler number, are both much large than unity. Although these conditions are satisfied at the exit, it is important to determine if the turbulence scales change close to the plate.

Shown in Fig.1 are the profiles of the time scales of the non-reacting stagnation point flow, t_x, obtained from auto-correlations and the associated length scale, l_x, deduced by Taylor's hypothesis for case #1. The length scale is relatively constant except at $x < 10$ mm where a decrease is found. This decrease seems to be an indication of the breakdown of the Taylor's hypothesis in the low velocity region. Similar features are also found in the turbulence generated by the perforated plate. Although it is not possible to deduce the integral length scale for the transverse component, the time scales show that the grid generated turbulence is isotropic whereas the turbulence generated by the perforated plate is slightly anisotropic with smaller transverse integral time scales. The result that both the length scale and the velocity fluctuations are constant[1] demonstrates that the flow criteria for current turbulent combustion models are satisfied even close to the stagnation flame region .

The mean centerline axial profiles of the conditioned and unconditioned velocities for case #1 are shown in Fig. 2. Also shown is the profile of the reaction progress variable. It shows that the reactant boundary of the flame zone, as indicated by the position where $\bar{c}$ deviates from zero, occurs at the minimum of the unconditioned velocity profile. This provides an experimental validation of our previous method of determining S_T where the minimum velocity was equated to the turbulent flame speed.[1]

The turbulent flame brush thickness, ∂_T, deduced from the $\bar{c}$ profiles is listed in Table I. Also listed is the corresponding laminar flame thickness,

∂_L, based on the definition of Zeldovich.[11] The ratio between the turbulent and laminar flame thicknesses is a significant parameter in the BML model which assumes infinite rate chemistry. Studies in turbulent v-flames and Bunsen flames have shown that at positions close to the stabilization region, the zero thickness flamelet assumption is not valid because the density pdf's show appreciable contributions from the intermediate burning states. These conditions are satisfied only at positions farther away because the flame brush thickness increases almost linearly with downstream distance. In contrast, since the stagnation flames do not have recirculating stabilization regions, the flame brush thickness remains relatively constant along the flame front. Therefore, the process of choosing a location suitable for comparison with theory is not encountered. Moreover, the smallest turbulent/laminar flame thickness ratio of 30 (case #2) indicates that the zero thickness flamelet approximation is valid for turbulent stagnation flames presently considered.

Another important aspect of the scalar field is the heat transfer to the stagnation plate. Since the plate is made of brass, the turbulent flame may be influenced by heat loss from the flame zone. To investigate the possible effect of heat loss, thermocouple measurements were made of the plate temperature and the thermal boundary layer over the plate. The results for case #4 show that, although the plate temperature is only 1500 K, the thermal layer thickness is about 3.0 mm, which is smaller than the standoff distance of the flame brush. This indicates that the wall effect is confined within the product region and is not expected to have any direct influence on flame propagation.

The features of the unconditioned axial velocity profile (Fig. 2) are typical of those measured in the stagnation flames as reported earlier.[1] The

unconditioned velocity profile shows distinct regions. The first region extends from the exit of the nozzle to the upstream boundary of the turbulent flame brush. It is characterized by a steady decrease in the axial velocity due to the divergence of the cold, unreacted flow. The global stretch rate imposed on the flow is given by the mean velocity gradient in this region. The second region is characterized by a rapid increase in velocity, indicating flow acceleration due to combustion heat release. The third region is where the product stream is again decelerated by the presence of negative pressure gradient and the flow eventually is brought to rest at the stagnation plate.

The upstream stretch rate, a, determined from these profiles (Table I) shows that the use of the grid tends to produce a slightly higher upstream stretch rate. This local stretch rate is of the same magnitude as local stretch rate on the flamelets, which can be estimated by u'/l_x. However, studies on laminar flames[12] have shown that such small stretch rates have minimal effect on the local burning rate.

Within the flame zone, the unconditioned mean velocity increases to form a "hump" at the product boundary as shown in Fig. 2. As discussed previously,[1] this increase is due to intermittent measurement of the conditioned velocities, $\bar{U}_r$ and $\bar{U}_p$. The relative velocity between the conditioned mean velocities, $\Delta U = \bar{U}_p - \bar{U}_r$, which is referred to as the slip velocity in the BML model, is a major contributor to the unconditioned fluctuations and the second and third order turbulent transport terms. The cause of the so-called counter gradient scalar transport is a direct result of the fact that ΔU is positive in most flames. Shown in Fig. 3 are the four ΔU profiles plotted against $\bar{c}$ obtained in this study. The data are normalized by the increase in velocity $\Delta u = S_L (\tau - 1)$ across a planar laminar flame where τ is the reactant/product density ratio. It can be seen the ΔU's are almost

constant and their values are about half of those of Δu. Previous measurements of this ratio in V-flames and conical Bunsen flames have shown that they are independent of $\bar{c}$ though they are generally lower than unity. As discussed by Cheng et. al.,[13] flow divergence in the products and random flow deflections due to the wrinkled flame would lower this ratio. However, the observation of constant $\Delta U/\Delta u$ ratio for different conditions in the stagnation flames is quite encouraging because it implies that the conditioned and unconditioned velocity profiles may be self-similar. This feature of the stagnation flame profiles would greatly facilitate the modeling of these flames. At present, similarity variables for the distance from the plate surface is proposed in BCL.[4] However, the proper means to nondimensionalize the velocity, however, requires further studies.

The conditioned and unconditioned rms fluctuation profiles for the axial and transverse components are shown in Fig. 4. The peak shown in the unconditioned u' profiles (Fig. 4(a)) represents contributions from ΔU. The more significant feature, however, is that the two axial conditioned rms fluctuations are almost equal. This suggests that there is no flame generated turbulence in the axial direction. The lack of a peak in the v' profiles is due to the fact that the transverse component of the relative velocity is zero. The difference in the conditioned fluctuations, $v'_p - v'_r$, is slightly higher at positions close to the product boundary than those shown for the axial component. Recent analysis of turbulence production across turbulent flamelets have shown that the increase in turbulence is associated with vorticity production.[7] Vorticity production is expressed by the baroclinic term which is the cross product between the pressure gradient normal to the flamelet and the local flame curvature due to stretch. In the stagnation flame the adverse mean axial pressure gradient may, by reducing the magnitude

of the baroclinic term, suppress production of vorticity. It is, however, important to emphasize the tentative nature of this interpretation, pending further experimental evidence and theoretical analysis.

The lack of significant flame generated turbulence, in particular in the axial fluctuations, also has a significant impact on the modeling of the third order turbulent transport terms. For example, the turbulent diffusion of scalar is modeled[8] as

$$\frac{\overline{\rho u''^2 c''}}{\bar{\rho}} = \bar{c}(1-\bar{c})\{(\bar{U}_p-\bar{U}_r)^2[\bar{c}^2+(1-\bar{c})^2]-\overline{u'^2_r}+\overline{u'^2_p}\}$$

the turbulence flux is

$$\frac{\overline{\rho u''^3}}{\bar{\rho}} = (1-\bar{c})\{3(\bar{U}_r-\bar{U})\overline{u'^2_r}+(\bar{U}_r-\bar{U})^3+\overline{u'^3_r}\}+\bar{c}\{3(\bar{U}_p-\bar{U})\overline{u'^2_p}+(\bar{U}_p-\bar{U})^3+\overline{u'^3_p}\}$$

where

$$\bar{U} = \bar{c}\bar{U}_p + (1-\bar{c})\bar{U}_r$$

These sub-models consist of contributions from ΔU, the difference in the conditioned turbulence intensities, and the third order terms. However, as the conditioned velocity pdf's are essentially Gaussian, these third order terms may be neglected.[8] In previous theoretical studies, Bray et. al.[3] used an empirical constant to relate the increase in the conditioned velocity fluctuations. To study the relative contributions from the two terms, the ratios $(u'_p{}^2 - u'_r{}^2)/(\Delta U)^2$ and $(v'_p{}^2 - v'_r{}^2)/(\Delta U)^2$ are plotted in Fig. 5. As can be seen the magnitudes of these ratio are very small, although $(v'_p{}^2 - v'_r{}^2)/(\Delta U)^2$ tend to be slightly higher than $(u'_p{}^2 - u'_r{}^2)/(\Delta U)^2$ for cases #3 and #4. The lack of significant turbulence production by the flame suggests that all the third order transport can be modeled simply by considering the contributions from the relative velocity ΔU. This again simplifies the modeling scheme.

Concluding Remarks

Reported in this paper is a detailed experimental investigation of the characteristics of the velocity and scalar fields in stagnation flow stabilized premixed turbulent flames. This relatively new turbulent flame configuration is considered to be the most suitable for direct comparisons between experimental and theoretical predictions. The measurements include conditioned and unconditioned velocity statistics of two components, and the profiles of mean reaction progress variable which is identical to the normalized density in the limit of zero thickness flamelet assumption. The turbulence Reynolds numbers and Damkohler numbers for the four methane/air flames indicate that these flames are within the wrinkled flamelet regime. The experimental results are analyzed to provide insight which will assist in the development of the Bray-Moss-Libby flamelet model for these flames.

For all the flow and mixture conditions considered here, the relative velocity ΔU between the reactants and products, i.e. the difference in the conditioned velocities is constant across the flame brush. Moreover, the relative velocities, when normalized by the velocity increase, $\Delta u = S_L(\tau-1)$, under laminar condition, have the same value. This suggests that the mean unconditioned velocity profiles across the flame region are self-similar. These characteristics, if confirmed by more extensive studies, would greatly simplified the modeling of the complex turbulent flame flow field.

Within the flame brush, the conditioned turbulence intensities for the axial and transverse velocity components are about equal and constant. That is, the stagnation flames do not create additional turbulence. This is quite different form the results obtained in oblique flames where flame generated turbulence occurs. The most important implication to modeling is that all the second and third order turbulence transport terms are reduced to functions of

the relative velocity ΔU. This again implies self-similarity of the turbulence and transport properties.

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Table I

Mixture and flow conditions

Case #	Turbulence generator	u' (cm/s)	length scale (mm)	stretch rate (sec^{-1})	ϕ	Re_ℓ	Da	δ_T (mm)	δ_L (mm)	S_T (cm/s)
1	grid	30	2	145	1.0	38	20	5.8	0.12	95
2	grid	30	2	115	0.9	38	14	4.4	0.14	60
3	plate	45	3	110	1.0	87	20	10.4	0.12	135
4	plate	45	3	100	0.9	87	14	8.3	0.14	120

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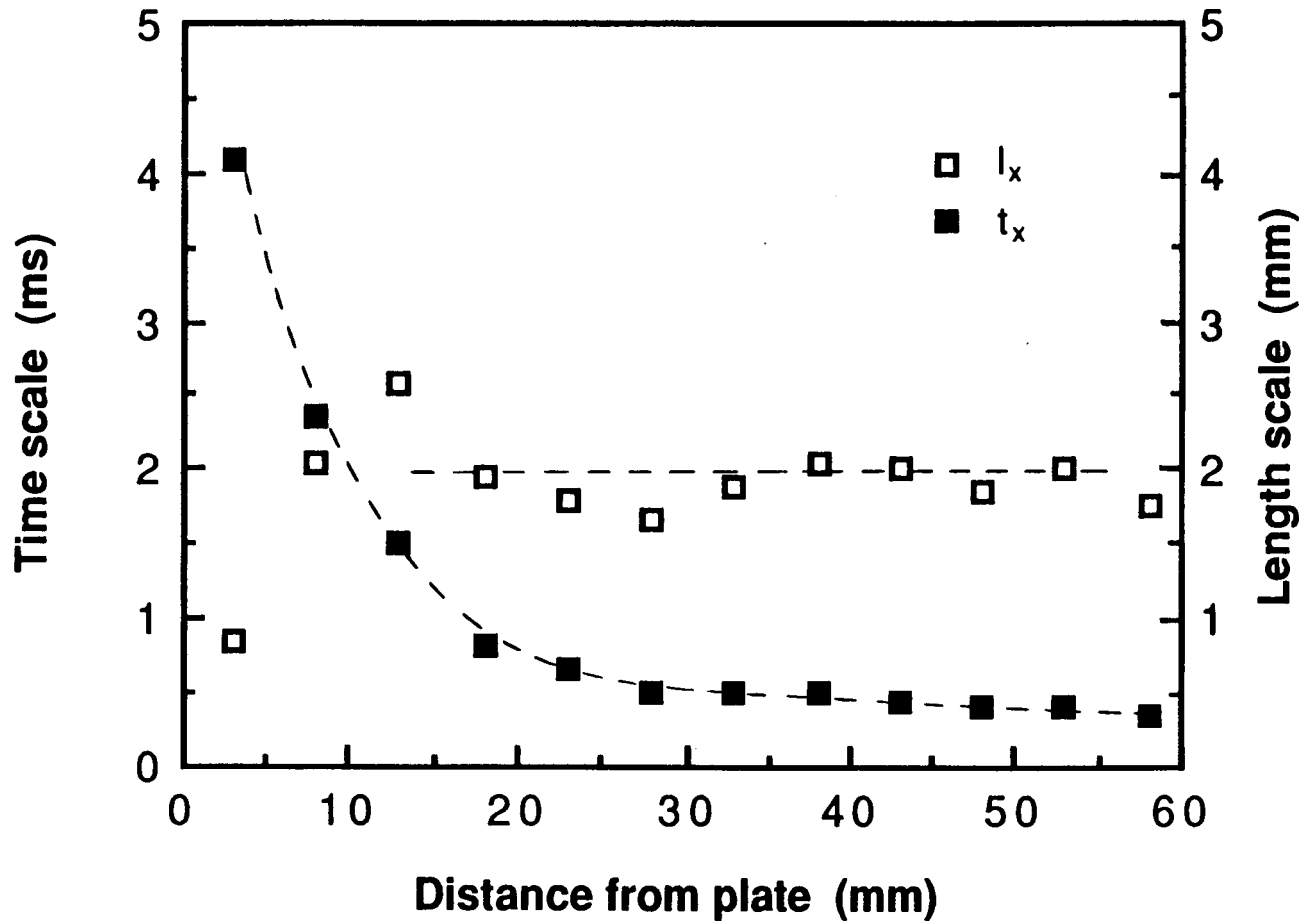
Figure 1. The time scales of the non-reacting stagnation flow, t_x, obtained from auto-correlation and the associated length scale, l_x, obtained by Taylor's hypothesis.

Figure 2. Mean centerline axial profile of the conditioned and unconditioned velocities for case #1 (Ø=1 and u'=40 cm/s). Inset: profile of the reaction progress variable.

Figure 3. Dependence of the normalized slip velocity as a function of the reaction progress variable.

Figure 4. Conditioned and unconditioned rms velocity fluctuations for (a) axial, and (b) transverse components.

Figure 5. Relative importance of the first and second moments of conditioned velocities of (a) axial, and (b) transverse components.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Length scale (mm)
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t_x
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40
50
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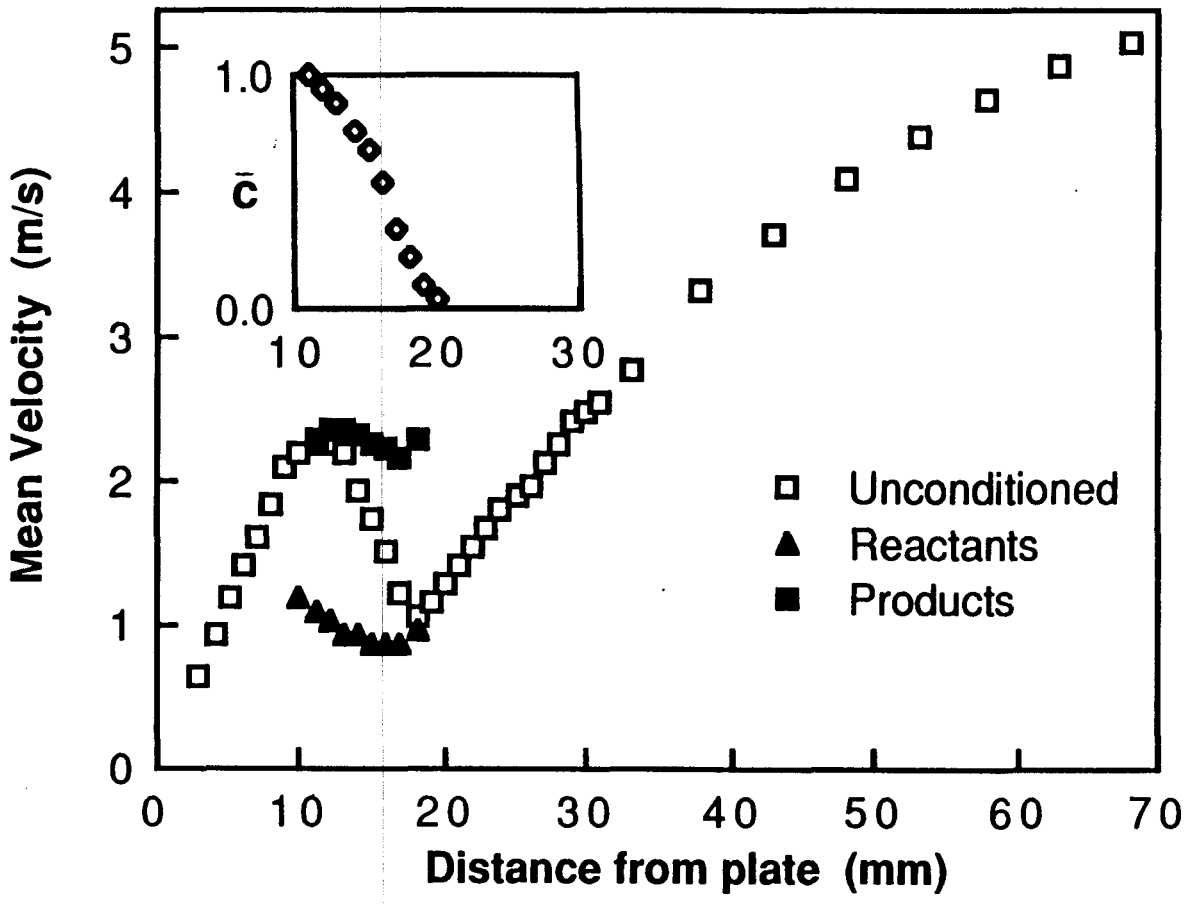
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Distance from plate (mm)
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2
3
4
5
0
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$\bar{c}$
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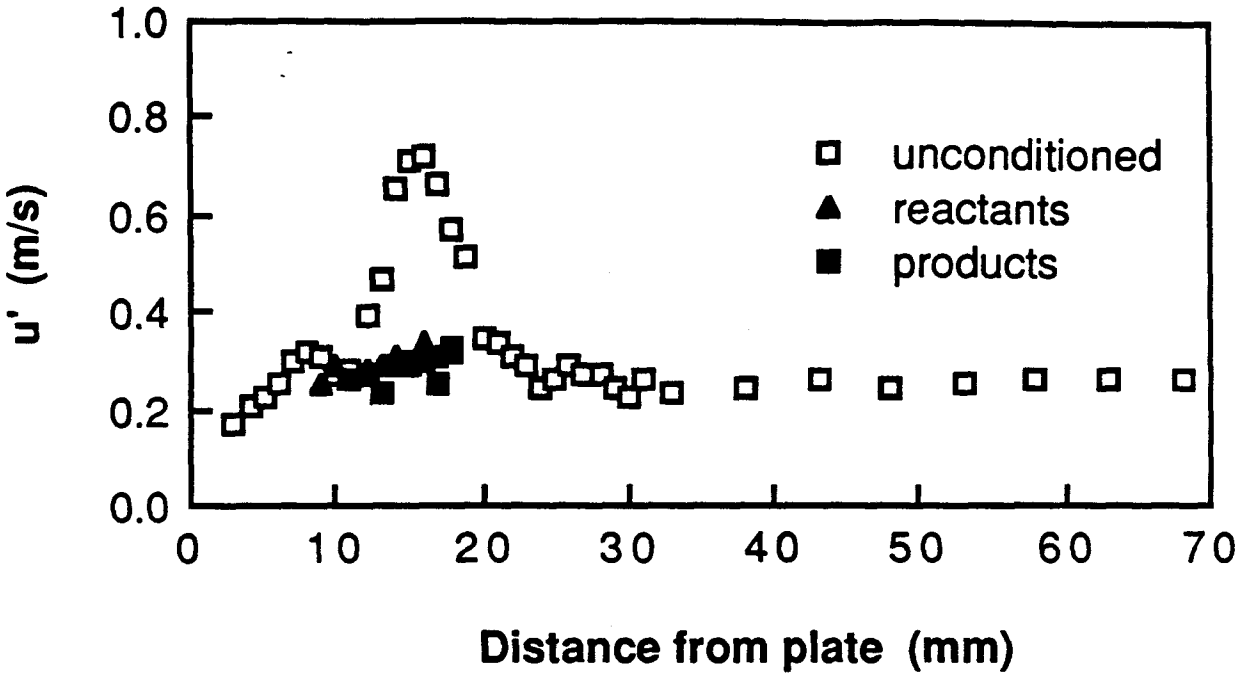
Unconditioned
Reactants
Products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50
60
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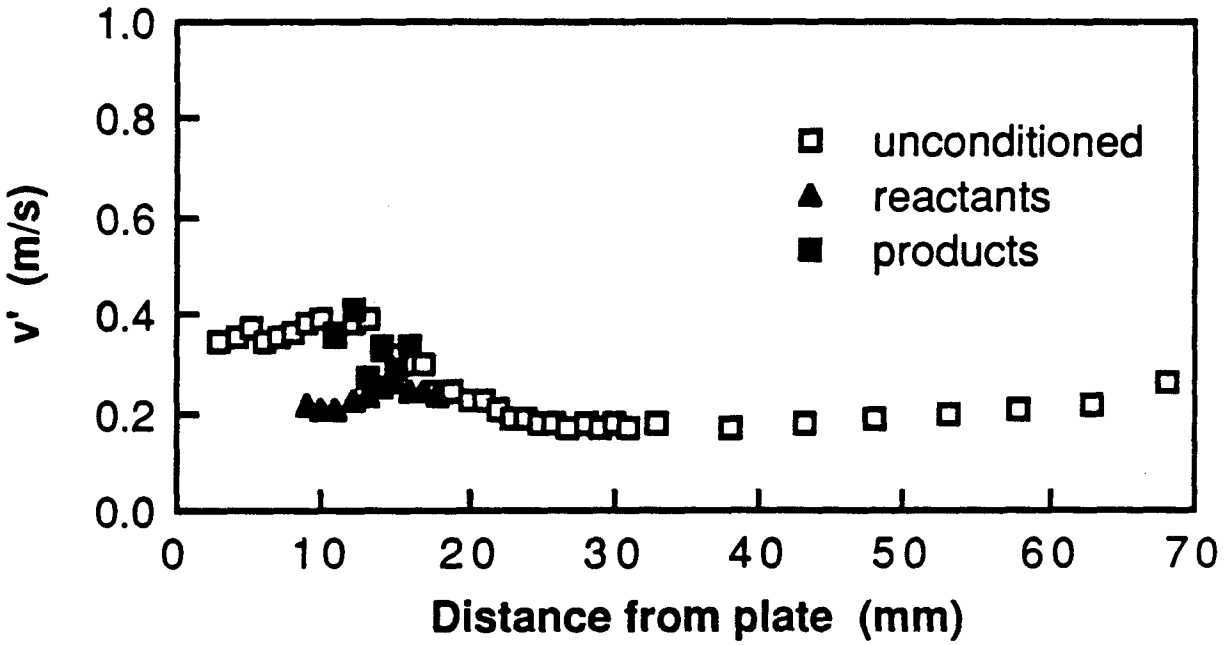
Distance from plate (mm)

(a)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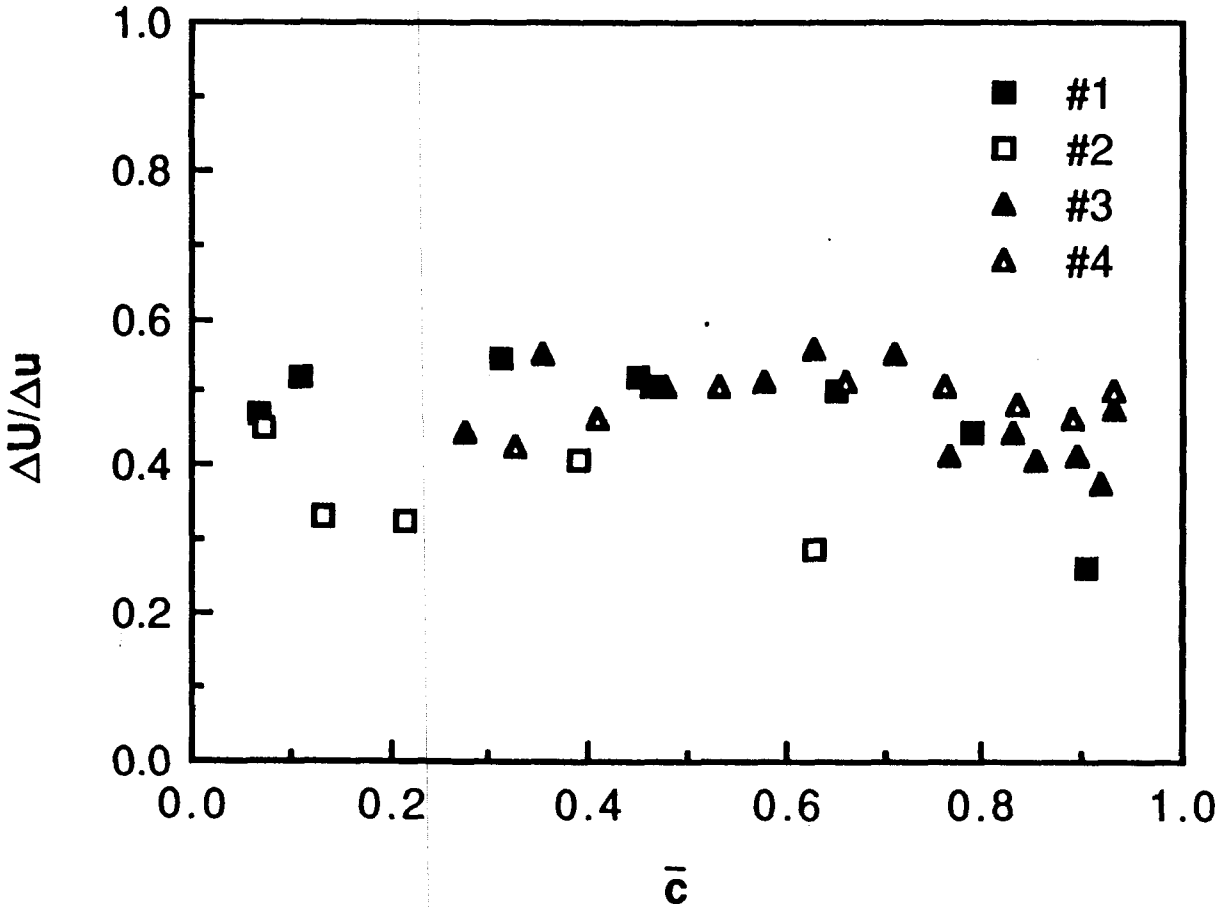
Distance from plate (mm)

(b)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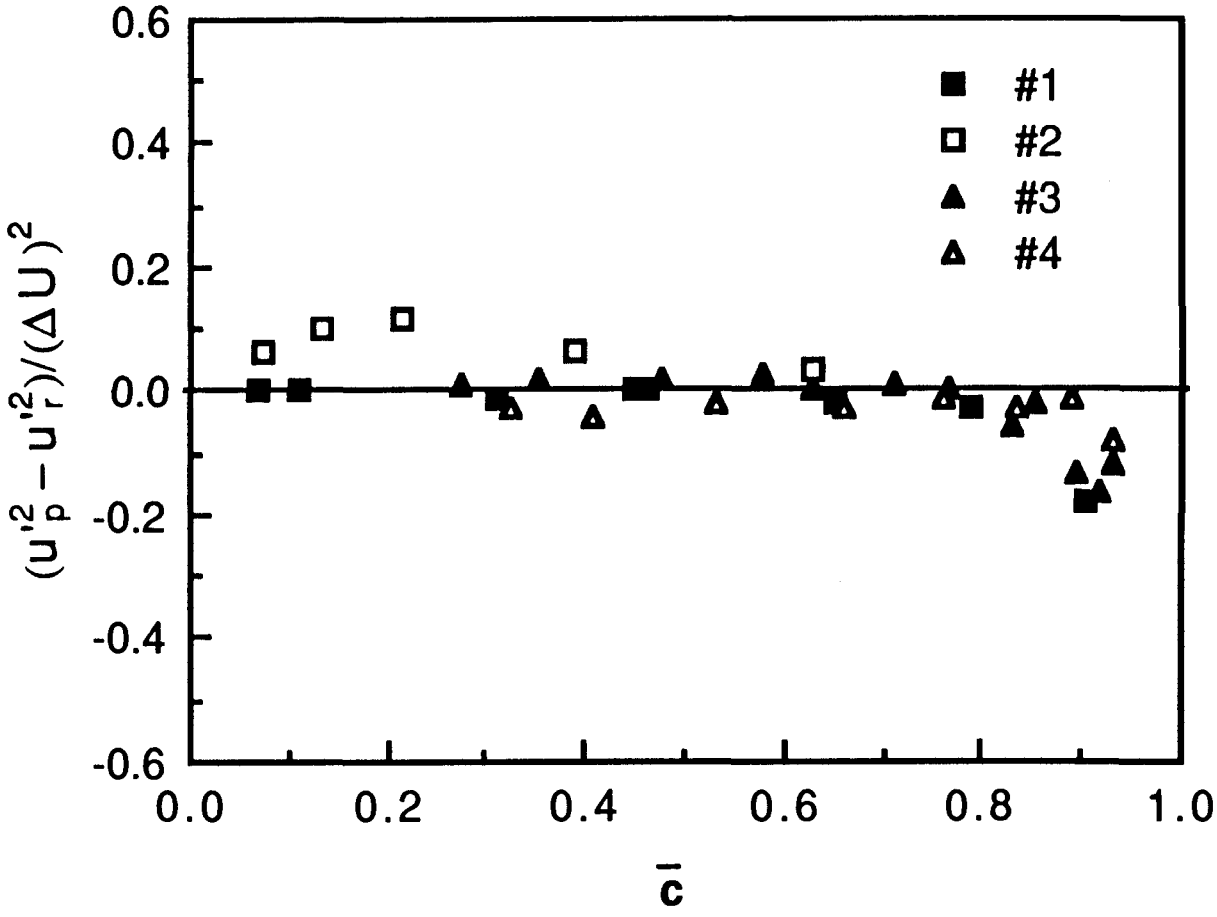
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$\bar{c}$
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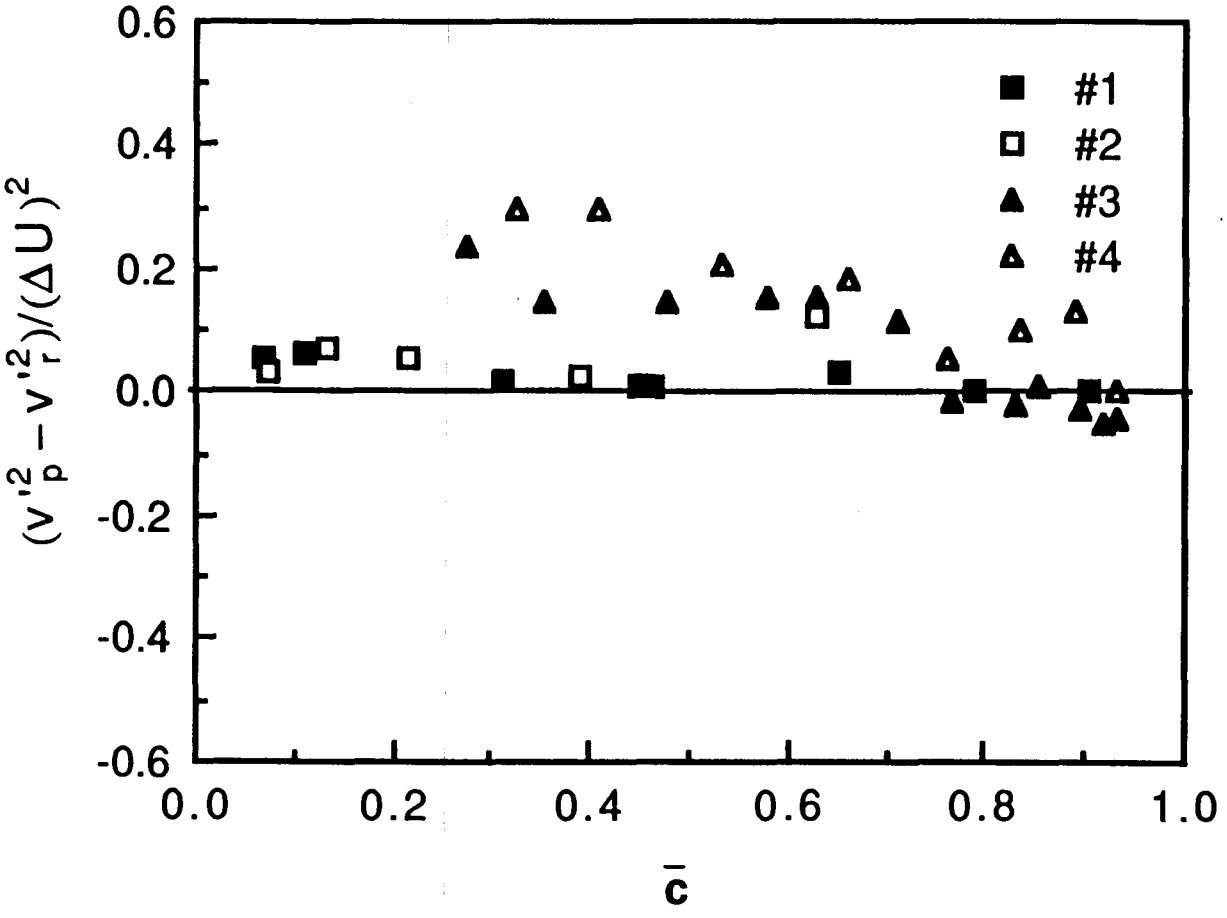
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$(v_p'^2 - v_r'^2)/(\Delta U)^2$
$\bar{c}$
#1
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