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NONGRADIENT DIFFUSION IN PREMIXED TURBULENT FLAMES

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Abstract - We review recent theoretical and experimental results demonstrating the interaction between force fields and density inhomogeneities as they arise in premixed turbulent flames. In such flames the density fluctuates between two levels, the high density in reactants ρ_r and the low density in products ρ_p with the ratio ρ_r/ρ_p on the order of five to ten in flows of applied interest. The force fields in such flames arise from the mean pressure drop across the flame or from the Reynolds shear stresses in tangential flames with constrained streamlines. The consequence of the interaction is nongradient turbulent transport, countergradient in the direction normal to the flame and nongradient in the tangential direction. The theoretical basis for these results, the presently available experimental support therefor and the implications for other variable density turbulent flows are discussed.

INTRODUCTION

The phenomenology of turbulent flows is largely based on gradient transport assumptions proposed over a century ago by de St. Venant and/or Boussinesq. Even in the recently exploited second moment methods of analysis, methods which involve large systems of partial differential equations calling for considerable computational effort, closure is achieved by employing gradient models to eliminate third moment and other quantities. The extension to turbulent flows with variable density of the various gradient models carefully developed and validated for constant density turbulence has unfortunately been casually undertaken with the consequence that much additional research is needed before the phenomenology is well founded for high speed turbulent boundary layers and jets and for turbulent reacting flows, both high and low speed. That new significant processes may be operative in turbulent flows with variable density is suggested by the recent findings in premixed turbulent flames. It is our purpose to review these findings and to discuss their implications.

Exposition is facilitated if we consider a normal premixed turbulent flame as shown schematically in Fig. 1. Cold reactants, a metastable mixture of fuel and oxidizer, with a mean velocity $\bar{u}_o$, a density ρ_r, an intensity of velocity fluctuations characterized by a turbulent kinetic energy k_o and a length scale of the large eddies l_o are consumed within the flame and exit as hot products with these quantities changes to $(1 + \tau)\, \bar{u}_o$, ρ_p, k_∞ and l_∞ respectively. Here τ is a heat release parameter with values of practical interest from five to ten. Figure 1 may be considered an idealization of the flames which occur in internal combustion engines, various propulsion systems involving prevaporized fuels and industrial accidents.

The object of a theory for such flames is the prediction of the turbulent flame speed $\bar{u}_o$ and of the flame structure. The development of such a theory involves two related considerations; one concerns the thermochemistry of the flow, the description of the state of the gas, its density, temperature and composition, while the second relates to fluid mechanics. These two aspects are the aerothermochemistry of the flow.

Various parameters can be used to characterize these flames. One system is proposed by Abraham *et al.* (1985) and involves a Damköhler number $Da_\Lambda \equiv (\Lambda/u')\,(S_L/\delta_L)$ where Λ is a large eddy scale, i.e., l_o introduced earlier, $u' \approx (3/2\, k_o)^{1/2}$ is a characteristic intensity of the velocity fluctuations and S_L and δ_L are the speed and thickness respectively of an unstrained laminar flame in the chemical system under consideration. A second parameter is a turbulent Reynolds number $R_\Lambda \equiv u'\,\Lambda/\nu$ where ν is a representative kinematic viscosity.* A pair of values, Da_Λ and R_Λ, determines the ratio of two velocities u'/S_L and of two lengths L_K/δ_L where L_K is a characteristic Kolomogoroff length. For premixed turbulent flames within internal combustion engines Abraham *et al.* (1985) determine that $1 < (L_K/\delta_L) < 10^2$. The implication of this finding is that chemical reaction at the molecular level takes place in thin surfaces, laminar flamelets, whose structure is dominated by laminar transport and whose motion is determined by the turbulent velocity field. Similar considerations applied to other premixed turbulent flames indicate that in many, indeed most, applications of applied interest this laminar flamelet description prevails.

The Bray-Moss Model and Some Consequences

Although not restricted to flows involving such flamelets, the Bray-Moss (BM) model simply and with an accuracy suitable for many purposes describes the thermochemistry of premixed turbulent flows (cf. Bray and Moss 1975). According to this description the instantaneous value of a progress variable $c(\underset{\sim}{x},t)$ which has the values zero in reactants, unity in products and intermediate values in gas possibly undergoing chemical reaction determines the entire state of the gas. Thus, for example,

$$\frac{\rho}{\rho_r} = \frac{1}{1+\tau c} \qquad \frac{T}{T_r} = 1 + \tau c \tag{1}$$

where τ is most readily determined from the specialization of the second of these equations to products, i.e., from

$$\frac{T_p}{T_r} = 1 + \tau \tag{2}$$

* It should be kept in mind that ν can vary by one to two decades within a flame and thus that there is some ambiguity as to its appropriate value for determining R_Λ.

In averaging the equations for variable density turbulent flows it is useful to employ Favre or mass averaging; to illustrate the notion and notation involved consider the i-th velocity component, namely

$$u_i(\underset{\sim}{x},t) = \frac{\overline{\rho u_i}}{\bar{\rho}}(\underset{\sim}{x}) + u''(\underset{\sim}{x},t) = \tilde{u}(\underset{\sim}{x}) + u''(\underset{\sim}{x},t)$$

All variables except the density and pressure are averaged in this fashion. The great advantage of Favre averaging is that the conservation equations for variable density flows closely resemble those for constant density with exceptions which, as we shall see, indicate special effects associated with the variability of the density. Despite this advantage it should not be assumed without support from experiment that the closure methods applicable to constant density flows can be carried over to variable density cases without modification. Furthermore, although significant only when low turbulence Reynolds numbers must be taken into account, Favre averaging is not adaptable without approximation to the molecular terms in the conservation equations. The definitive discussion of Favre averaging applied to turbulent combustion is given by Jones (1980) while such averaging is emphasized in the monograph on turbulent reacting flows by Libby and Williams (1980). Rubesin and coworkers at the Ames Research Center of NASA apply Favre averaging for the analysis of high speed turbulent boundary layers (cf. Wilcox and Rubesin 1980).

When Favre averaging is applied to Eqs. (1), there results

$$\frac{\bar{\rho}}{\rho_r} = \frac{1}{1+\tau\tilde{c}} \qquad \frac{\tilde{T}}{T_r} = 1 + \tau\tilde{c} \tag{2}$$

A further important feature of the BM model is an approximation for the probability density function (pdf) of the progress variable. In general for a statistically stationary flow

$$P(c;\underset{\sim}{x}) = \alpha(\underset{\sim}{x})\,\delta(c) + \beta(\underset{\sim}{x})\,\delta(1-c) + \gamma(\underset{\sim}{x})\,f(c;\underset{\sim}{x}) \tag{3}$$

Now if

$$\int_{0^+}^{1^-} dc\ f(c;\underset{\sim}{x}) = 1$$

i.e., if the pdf describing the interior values of the progress variable is normalized, then

$$\alpha(\underset{\sim}{x}) + \beta(\underset{\sim}{x}) + \gamma(\underset{\sim}{x}) = 1 \tag{4}$$

The essential approximation in the BM-model is that $\gamma \ll 1$, an approximation which is satisfied when chemical reaction occurs in laminar flamelets as well as in other flow structures, e.g., reaction zones with $\delta_L > L_K$. The implication of this approximation is that the temperature as measured by an idealized thermometer within a premixed turbulent flame possesses essentially two values, T_r within reactants and T_p within products, and that flamelet passages cause the switch from one level to the other.*

An important consequence of the $\gamma \ll 1$ approximation is exposed if $\tilde{c}(\underset{\sim}{x})$ is calculated from Eq. (3). There results

$$\alpha(\underset{\sim}{x}) = \frac{1-\tilde{c}}{1+\tau\tilde{c}} \qquad \beta(\underset{\sim}{x}) = \frac{(1+\tau)\,\tilde{c}}{1+\tau\tilde{c}} \tag{5}$$

where Eq. (4) is used to calculate $\alpha(\underset{\sim}{x})$. We thus see that the strengths of the delta functions is simply related to the mean value of the progress variable which must be considered one of the principal dependent variables in a theory of premixed turbulent flames.

For the present discussion it is useful to consider the intensity of the density fluctuations; from Eqs. (1), (3) and (5) we can compute

$$\frac{\overline{\rho'^2}}{\bar{\rho}^2} = \tau^2\,\frac{\tilde{c}\,(1-\tilde{c})}{1+\tau} \tag{6}$$

We thus see that the maximum in the relative intensity of the density fluctuations occurs within the flame where $\tilde{c} = 1/2$ and has a value $\tau^2/4(1+\tau) \simeq \tau/4$ for $\tau \gg 1$. Thus for degrees of heat release of applied interest we must expect intense density fluctuations.

Although not essential for the present discussion, it is worth noting that the mean rate of creation of product $\bar{w}(\underset{\sim}{x})$ in the BM model involves the product $\gamma w_{\max}$ where $w_{\max}$ is the maximum rate of creation of product, a quantity determined by the chemical kinetics of the system under consideration. In the BM model this product involves a vanishingly small term multiplied by an indefinitely large term and is thus

* Extensive studies of the statistics of two valued functions with specific reference to premixed turbulent flames have been carried out in order to develop a model for the mean rate of creation of product (cf. Bray *et al.* 1987).

indeterminant. As a consequence a separate model for $\overline{w}(\underset{\sim}{x})$ is needed; progress in this direction is described in Bray *et al.* (1987).

The Bray-Moss-Libby Model for the Aerothermochemistry

The notion of bimodality extends to the the description of the velocity components in premixed turbulent combustion and leads to the Bray-Moss-Libby (BML) model of the aerothermochemistry of such combustion. To appreciate this extension consider the bivariate pdf

$$P(u_i, c; \underset{\sim}{x}) = \alpha(\underset{\sim}{x})\, \delta(c)\, P(u_i, 0; \underset{\sim}{x}) + \beta(\underset{\sim}{x})\, \delta(1-c)\, P(u_i, 1; \underset{\sim}{x}) +$$

$$\gamma(\underset{\sim}{x})\, f(u_1, c; \underset{\sim}{x}) \tag{7}$$

Figure 2 shows schematically such a joint pdf. If $f(u_i, c; \underset{\sim}{x})$ is normalized, Eq. (4) again applies and with the approximation $\gamma \ll 1$ the statistical behavior of u_i and c are again dominated by contributions from reactants and products. Note that two of the three pdf's on the right side of Eq. (7) are conditional and describe the velocity within reactants and products. It is possible with current diagnostic techniques to measure with good spatial resolution the temperature and one or more velocity components and thus to determine experimentally the conditional pdf's appearing in Eq. (7) (cf. Moss 1980 and Shepherd and Cheng 1988).

Equation (7) leads to significant results if $\gamma \ll 1$. To illustrate consider the mean *unconditional* velocity component $\tilde{u}_i(\underset{\sim}{x})$ which is given by Eqs. (5) and (7) as

$$\tilde{u}_i(\underset{\sim}{x}) = (1 - \tilde{c})\, \overline{u}_{ir} + \tilde{c}\, \overline{u}_{ip} \tag{8}$$

where $\overline{u}_{ir}$ and $\overline{u}_{ip}$ are the *conditional* mean values of the i-th velocity component within reactants and products respectively. We show these values in Fig. 2. Precise definitions of these quantities are as follows:

$$\overline{u}_{ir}(\underset{\sim}{x}) = \int_{-\infty}^{\infty} du_i\, u_i\, P(u_i, 0; \underset{\sim}{x})$$

$$\bar{u}_{ip}(\underset{\sim}{x}) = \int_{-\infty}^{\infty} du_i \; u_i \; P(u_i, 1; \underset{\sim}{x}) \tag{9}$$

According to the BM model the mean turbulent flux of all state variables in the i-th coordinate direction can be determined from the corresponding flux of the progress variable but from Eq. (7) we have

$$\frac{\overline{\rho u_i'' c''}}{\bar{\rho}} = \tilde{c}\,(1-\tilde{c})\,(\bar{u}_{ip} - \bar{u}_{ir}) \tag{10}$$

Now a gradient model for this mean flux yields

$$\frac{\overline{\rho u_i'' c''}}{\bar{\rho}} = -\nu_T \frac{\partial \tilde{c}}{\partial x_i} \tag{11}$$

where ν_T is a positive turbulent exchange coefficient. If in connection with Fig. 1 we let x_i correspond to x, then $\partial \tilde{c}/\partial x > 0$ implying that $\overline{\rho u'' c''} < 0$ and if gradient transport applies, then $\bar{u}_p < \bar{u}_r$. But we know from our earlier discussion that the velocity in the product stream downstream of the flame where $\tilde{c} = 1$ is $(1+\tau)$ times greater than that in the reactant stream. Given this overall increase in mean velocities it does not seem reasonable to expect the conditional velocities in products within the flame to be less than those within reactants. Accordingly, we see a potential difficulty with a gradient model for premixed turbulent flames if, as is the case in flames of practical interest, $\tau \gg 1$.

In Bray *et al.* (1981), Masuya and Libby (1981) and Libby (1985) the BML model with all gradient assumptions avoided is applied to normal and oblique turbulent flames in premixed systems in order to clarify the applicability of the gradient model therein. In the next sections we sketch the analyses involved and review the results from them

APPLICATION TO NORMAL PREMIXED TURBULENT FLAMES

We now consider application of the notions advanced in the previous section to the flame of Fig. 1. The equations needed for the analysis are as follows:

$$\frac{d}{dx}(\bar{\rho}\,\tilde{u}) = 0$$

$$\frac{d}{dx}(\bar{\rho}\,\tilde{u}^2 + \overline{\rho u''^2}) = -\frac{d\bar{p}}{dx} \tag{12}$$

$$\frac{d}{dx}(\bar{\rho}\,\tilde{u}\;\tilde{c} + \overline{\rho u''c''}) = \bar{w}$$

and

$$\frac{d}{dx}\left[\bar{\rho}\,\tilde{u}\;\frac{\overline{\rho u''^2}}{\bar{\rho}} + \overline{\rho u''^3}\right] + 2\,\overline{\rho u''^2}\,\frac{d\tilde{u}}{dx} = -2\,\overline{u''}\,\frac{d\bar{p}}{dx} - \bar{\chi}_u$$

$$\frac{d}{dx}\left[\bar{\rho}\,\tilde{u}\;\frac{\overline{\rho u''c''}}{\bar{\rho}} + \overline{\rho u''^2c''}\right] + \overline{\rho u''c''}\,\frac{d\tilde{u}}{dx} + \overline{\rho u''^2}\,\frac{d\tilde{c}}{dx} = -\overline{c''}\,\frac{d\bar{p}}{dx} + \overline{u''w} - \bar{\chi}_{uc} \tag{13}$$

The usual notation applies to Eqs. (12) and (13) which represent the first and second moment equations respectively for one dimensional flames. The quantities $\bar{\chi}_u$ and $\bar{\chi}_{uc}$ describe dissipation effects which for the flames under consideration are due solely to chemical reaction, i.e., are proportional to $\bar{w}$. Similarly the velocity-chemical reaction term $\overline{u''w}$ can be convincingly described by application of the BML model; it is found to be proportional to $\bar{w}$, models for which are presently under development (cf. Bray *et al.* 1987) but which are not needed for present purposes.*

Some analysis permits Eqs. (12) and (13) to be reduced to two equations with $\tilde{c}$ as the *independent* variable and with a dimensionless velocity intensity $I \equiv \overline{\rho u''^2}/\rho_r\,\bar{u}_o^2$ and a dimensionless turbulent flux $F \equiv \overline{\rho u''c''}/\rho_r\,\bar{u}_o$ as the two *dependent* variables. In the present discussion the latter variable is of more significance. In this formulation $\bar{w}$ is needed only if subsequent to finding the solutions for $I(\tilde{c})$ and $F(\tilde{c})$ the spatial distributions are sought. However, comparison between theory and experiment is

* It is worth noting that in these equations the effects of pressure fluctuations are neglected. In constant density turbulence models for such effects have been painfully and carefully developed over a period of many years but these models do not apply to reacting flows with heat release since combustion induced pressure fluctuations result from volumetric sources, i.e., from an entirely different mechanism. Appropriate models for such fluctuations are not presently available.

conveniently carried out in terms of $\tilde{c}$ so that generally the absence of a model for $\bar{w}$ is not a shortcoming relative to the analysis of one dimensional flames. For premixed turbulent flows in two and three dimensions such a model is needed and research to that end is underway (cf. Bray *et al.* 1987).

In developing the final equations for $I(\tilde{c})$ and $F(\tilde{c})$ the first of Eqs. (2) and (12) permit $\tilde{u}$ to be eliminated while the second and third of Eqs. (12) are used to eliminate $d\bar{p}/dx$ and $\bar{w}$ respectively. Closure requires the third moment quantities $\overline{\rho u''^3}$ and $\overline{\rho u''^2 c''}$, $\overline{u''}$, $\overline{c''}$ and the dissipation terms to be expressed in terms of the two dependent and the independent variables but with the exception of some inessential uncertainties in the conditional velocity statistics suitable models for these quantities free of gradient assumptions can be developed. For example, we have

$$\overline{u''} = \tau \, \frac{\overline{\rho u'' c''}}{\rho_r} \qquad \overline{c''} = \tau \, \frac{\tilde{c}\,(1-\tilde{c})}{1+\tau\,\tilde{c}} \tag{14}$$

In the present discussion two terms in Eqs. (13) are of particular interest; we refer to those involving $d\bar{p}/dx$. If Eqs. (12) and (13) are specialized to constant density flows, e.g., by setting $\tau = 0$, then from Eqs. (14) we see that these terms vanish and indeed the reduction to standard equations for such flows is complete. The implication to be drawn from this consideration is that these pressure gradient terms account for effects operative in variable density turbulence, in particular an interaction between a force field associated with the pressure gradient and density fluctuations associated with heat release. In premixed turbulent flames this interaction is present only within the flame proper since both the force field and the density fluctuations are absent in the reactant and product streams on each side of the flame.

Additional comments on this interaction are indicated. If conventional rather than Favre averaging is used, the interaction is contained within the resulting equations but is obscured by the clutter of a large number of terms involving density fluctuations. In more general variable density flows models for the multipliers of the several pressure gradient terms must be introduced as indicated for nonpremixed combustion by Jones (1980) and for high speed flows by Wilcox and Rubesin (1980).

The final equations for $I(\tilde{c})$ and $F(\tilde{c})$ involve singularities at $\tilde{c} = 0,1$ as is to be expected since these points correspond to points at infinity in the x-variable but appropriate series expansions permit the numerical solutions to be initiated in the neighborhood of these end points. A shortcoming of the theory is that $I_o \equiv \overline{u'^2}_o/\bar{u}_o^2$ where $\overline{u'^2}_o$ is the intensity in the reactant stream upstream of the flame must be imposed, i.e., the turbulent flame speed is not calculated. This shortcoming can be turned into a virtue for the purpose of studying the structure of premixed turbulent flames since it can be argued that selection of I_o so as to achieve agreement with experimental results assures that the predicted flame structure corresponds to realistic flames. In our original work we set $I_o = 0.22$ unless we had specific reasons to do otherwise but in recent years our confidence in this value has been reduced by evidence that a wide variety of values is found depending on the geometry of the flames and on the flameholding mechanism employed. The detailed reasons for this ambiguity are unknown.*

Numerical Results for Normal Flames

In Fig. 3 we show the distribution of the turbulent flux in terms of $F(\tilde{c})$ from both theory and from the experiment of Moss (1980). In the open flame studied by Moss $\tau = 6.5$ and $I_o = 0.16$. The two curves represent theoretical predictions based on slightly different models for the conditional statistics, differences which are irrelevant for the present discussion. If it is recalled that gradient transport for these flames implies $F < 0$, we see that the entire flame structure exhibits countergradient diffusion. The explanation for such diffusion resides in the interaction between the pressure drop across the flame and the density fluctuations which from Eq. (6) are seen to involve a relative intensity greater than unity, roughly 1.4. The pressure drop tends to accelerate the light parcels of product relative to the heavy parcels of reactants in the direction of high product concentration, a differential effect contrary to gradient transport.

Several further comments are indicated. Calculations with the pressure gradient terms in Eqs. (13) suppressed yield $F < 0$ for all values of τ. Moreover, as $\tau \to 0$ the theory predicts gradient transport and thus the expected behavior for nearly constant density turbulent flows. These results lend credibility to the explanation of interaction as the cause of countergradient diffusion and to the validity of the theory in general. The notion of countergradient transport in premixed turbulent flames is now widely accepted

* A recent study (Libby 1987) removes the shortcoming with respect to I_o by invoking the Hakberg-Gosman condition and discusses in some detail the uncertainties in its value.

and has been observed in a variety of laboratory flames with simple geometries. Later we discuss its more general applicability.

THE OBLIQUE PREMIXED TURBULENT FLAME WITH CONSTRAINED MEAN STREAMLINES

In Fig. 4 we show schematically a premixed turbulent flame which is oblique to the reactant stream. Such flames can be established by a flameholder, e.g., a cylinder, in a duct carrying reactants. The classic experiment of this nature is due to Wright and Zukoski (1962) while the theoretical description of these flames based on the BML model is given by Masuya and Libby (1981). If we assume that the duct prohibits significant deflection of the mean streamlines both upstream and downstream of the flame, it is reasonable to consider as an idealization an infinite planar flame held at a specified angle θ with undeflected mean streamlines. In this case description of the flow involves an analysis identical with that for purely normal flames and a second, subsequent analysis of the tangential velocity component which involves explicitly the flame angle θ. The treatment of the tangential flow requires determination of the intensity of the fluctuations of the v-velocity component and the tangential flux of the progress variable which in dimensionless form are $I_v \equiv \overline{\rho v''^2}/\rho_r \bar{u}_o^2$ and $F_v \equiv \overline{\rho v'' c''}/\rho_r \, \bar{u}_o$ respectively. This latter variable is of principal concern in the context of the present discussion and from Eq.) is given by

$$\frac{\overline{\rho v'' c''}}{\bar{\rho}} = \tilde{c}\ (1 - \tilde{c})\,(\bar{v}_p - \bar{v}_r) \tag{15}$$

where $\bar{v}_r$ and $\bar{v}_p$ are the conditional tangential velocity components within reactants and products respectively.

Gradient transport indicates that this mean flux is zero since the tangential gradient of the progress variable is zero and thus that the two conditional velocities in the tangential direction are equal. The implication from this result is that parcels of reactants and products have streamlines which differ only by the differences in the normal conditional velocities. However, there is a tangential force field in these flames arising from the x-wise gradient of the Reynolds shear stress $\overline{\rho u'' v''}$; the existence of this forces field can be seen from the mean conservation equation for tangential momentum which yields

$$\frac{d}{dx}\,\overline{\rho u'' v''} = -\tau\,\frac{\rho_r\,\bar{u}_o^2}{\tan\theta}\,\frac{d\tilde{c}}{dx} \tag{16}$$

Note that when the heat release and thus the density fluctuations vanish, this force field is absent.

This discussion establishes that oblique turbulent flames in premixed systems involve a tangential force field and density fluctuations. Thus according to our previous argument we can expect nongradient turbulent transport in the tangential direction. Indeed calculations show that $\bar{v}_p > \bar{v}_r$, that $\overline{\rho v''c''} > 0$ and that the parcels of reactants and products follow different mean streamlines with the former exhibiting only small tangential velocity while the latter possesses large tangential velocities. This behavior is shown schematically in Fig. 4. We thus have an example of nongradient transport to add to the previously discussed case of countergradient transport. To date there have been no detailed measurements in oblique flames to assess the validity of this theory.

CONCLUDING REMARKS

We show that when mean force fields and density fluctuations coexist, an interaction leads to turbulent transport which is not described by the usual gradient model. In the simple flow configurations associated with normal and oblique planar flames, the latter with constrained mean streamlines, countergradient and nongradient transport exists. There is no question that the notions suggested by these findings are conceptually important. Moreover, the experimental results of Heitor *et al.* (1987) relative to the complex flow associated with a baffle stabilized premixed turbulent flame establish that nongradient transport exists in complex flow configurations, i.e., in flows of applied interest. Within the context of the present discussion the first few sentences of this paper are worth quoting:

> In turbulent, premixed flames there arise source terms, explicitly set out below, in the conservation equations for the turbulent heat transfer rate and stresses that have no counterparts in non-reacting flows. Analysis (Masuya and Libby 1981; Bray, Libby and Moss 1985; Libby 1985) has shown that at least in the two idealized extremes with the flame either normal or oblique to the approaching reactants, and at practically important levels of heat release, these terms are sufficiently large to cause non-gradient transport of turbulent heat flux. This finding is important because it casts doubt on the applicability of turbulence models that use gradient-transport hypothesis.

From a detailed study of the velocity and temperature fields Heitor *et al.* conclude that the interaction between pressure gradients and density fluctuations results in the largest contribution to the balance of the turbulent heat flux and that that flux is not aligned with the mean temperature gradient.

The importance of nongradient transport on general variable density turbulence remains to be established. With respect to premixed turbulent flames we note that the question arises as to the influence of these processes arising within their structure on their orientation between reactant and product streams remains to be clarified. Answering this question requires further theoretical and computational efforts.*

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* If the provisional model for $\widetilde{W}(\underset{\sim}{x})$ set forth in Bray *et al.* (1987) is validated, the effort required is largely computational.

Additional research is also required to determine the importance of the interaction under discussion in high speed flows. It would seem obvious that in scramjets with their large gradients of mean pressure and mean turbulent shear stresses this interaction must be operative but whether it plays an important role in the mixing and chemical processes in the flow is unclear. Certainly the present casual, uncritical extension to supersonic chemically reacting flows of the phenomenology of constant density turbulence should raise healthy skepticism concerning the validity of the resulting predictions but unfortunately that skepticism does not appear to be shared by authors, reviewers and editors of current journal articles.** Similar uncertainties would appear to prevail for turbulent boundary layers in high speed flows so that additional research is indicated.

** Occasionally there is a mild rejoinder warning the reader of potential fundamental difficulties. An example from a recent report is as follows: "The turbulence model we we have used is the $k - \varepsilon$ model as described in ... Although Reference ... specifically addresses the question of compressible flows, it should be noted that turbulence models for compressible flows are not well-developed. Hence, the choice of the standard $k - \varepsilon$ model in this situation cannot be regarded as definite."

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2. The joint probability density function (From Libby 1985)

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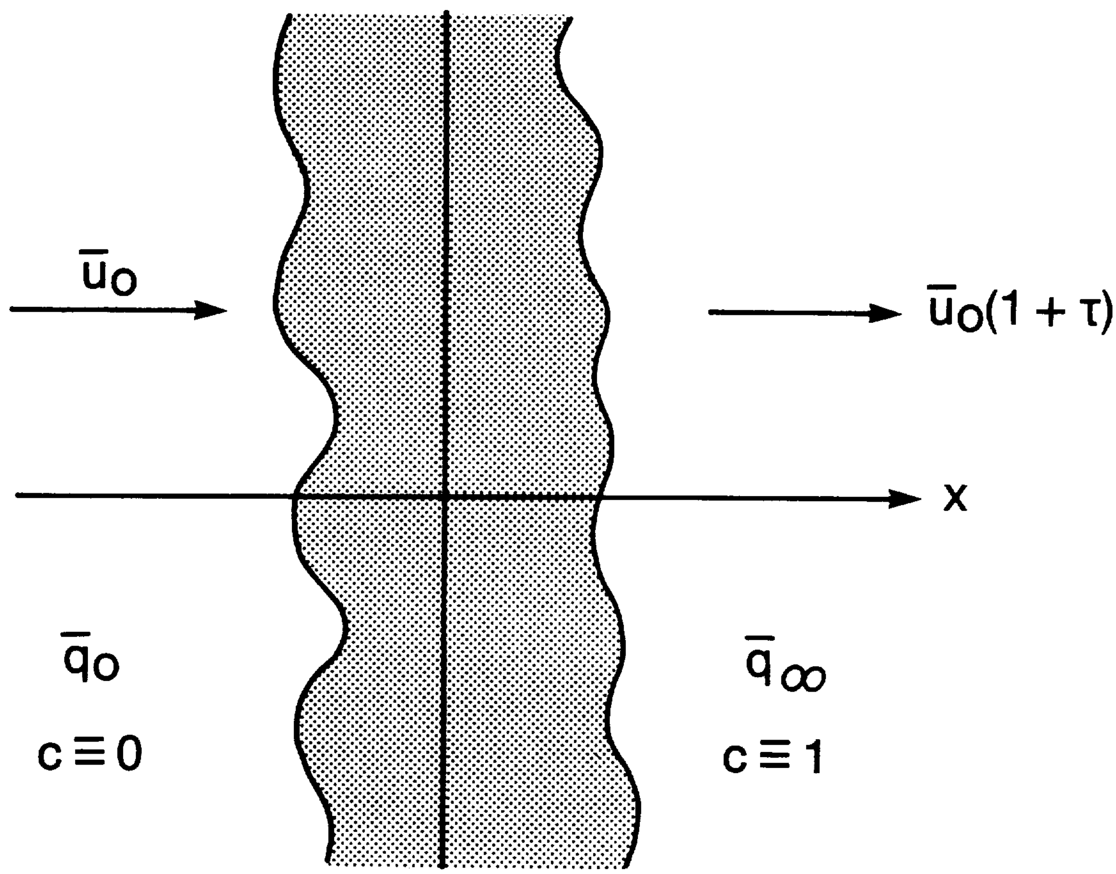
4. Schematic representation of a premixed turbulent flame oblique to the reactant stream and with constrained mean streamlines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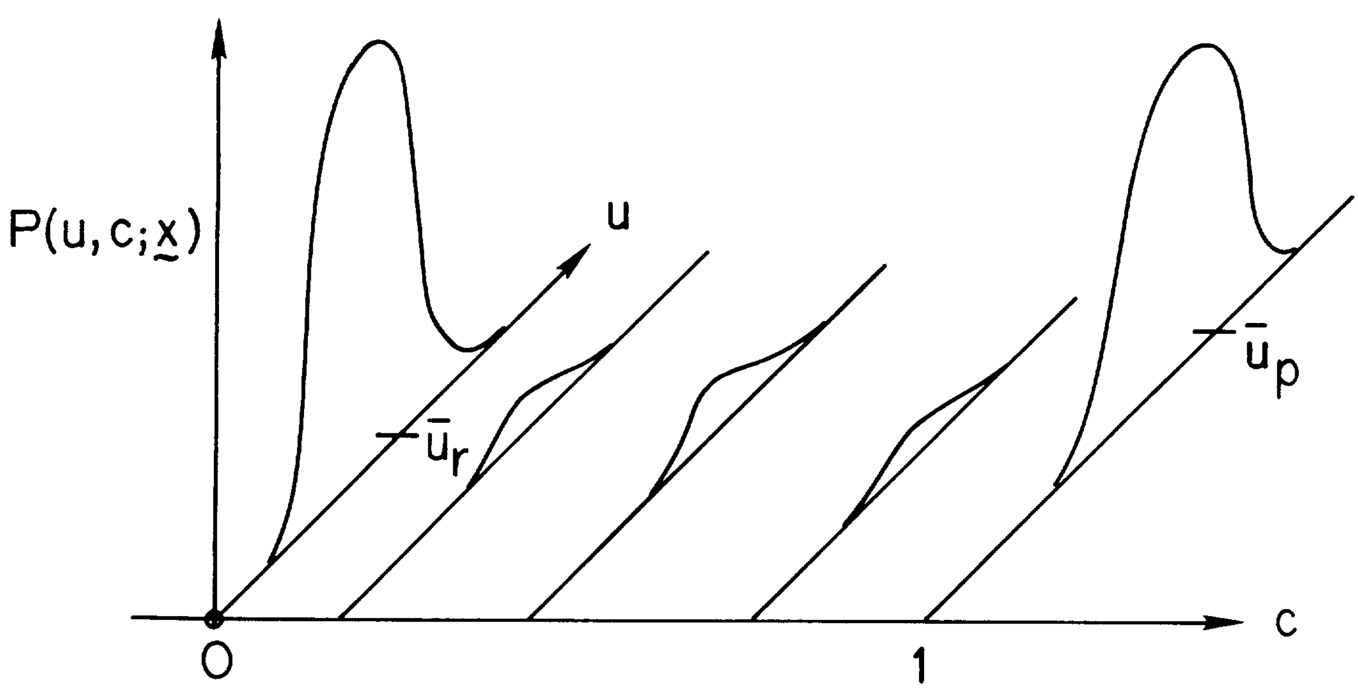

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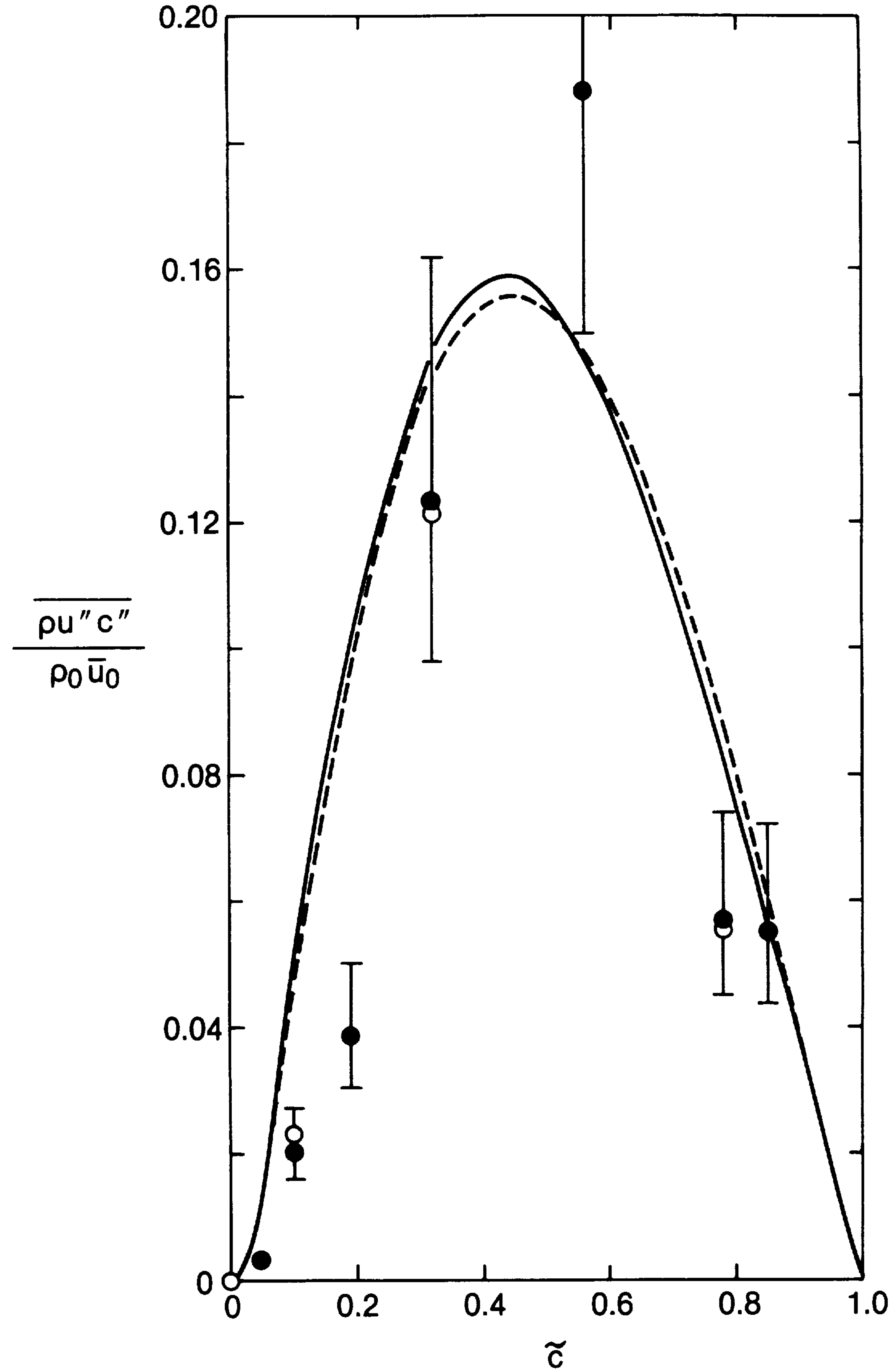
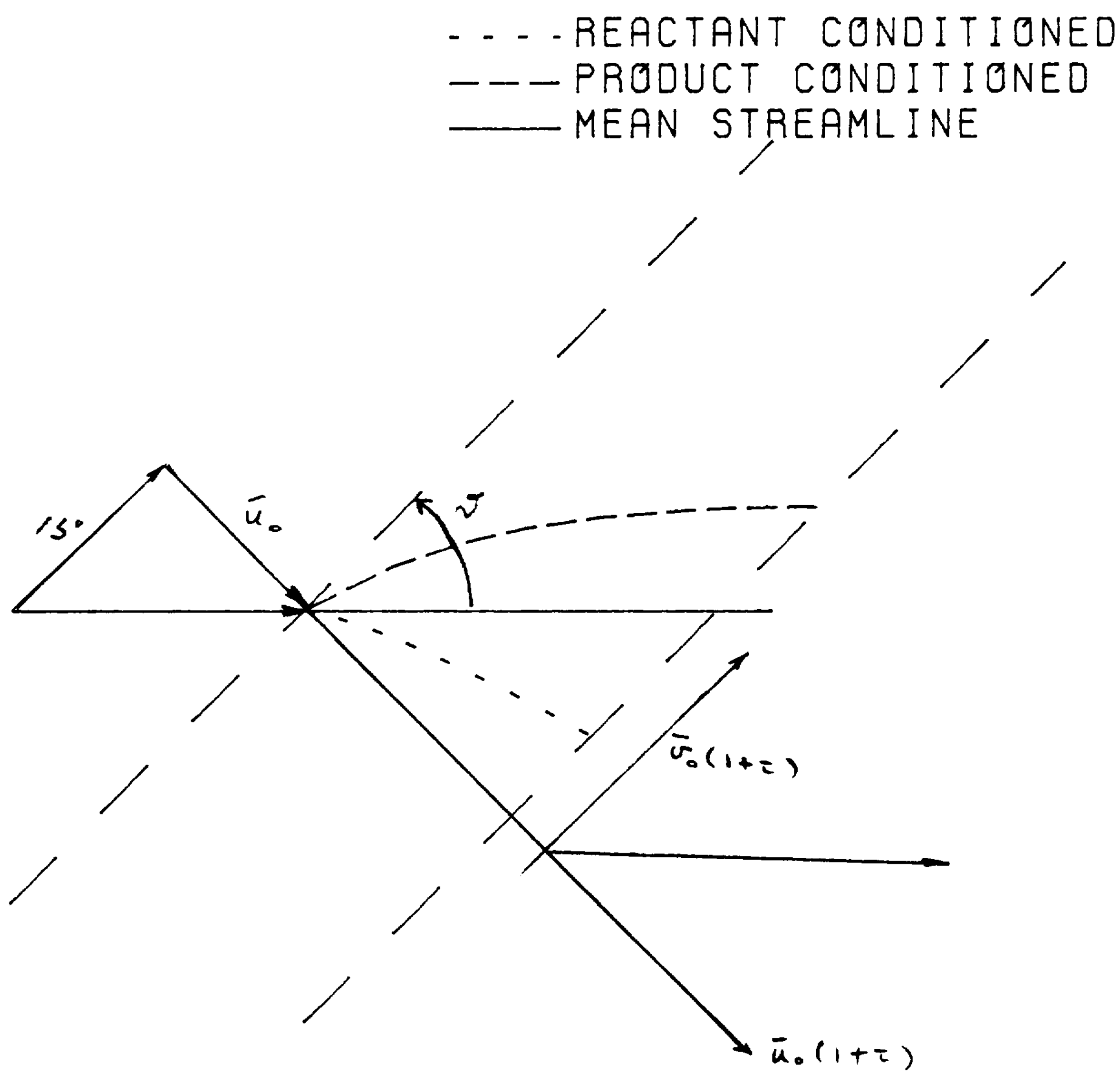

0.20
0.16
0.12
0.08
0.04
0
$\frac{\overline{\rho u'' c''}}{\rho_0 \bar{u}_0}$
0
0.2
0.4
0.6
0.8
1.0
$\tilde{c}$



confined oblique flame