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SEEDING PROBLEMS IN FLAMES & SWIRLING FLOWS, WITH IMPLICATIONS FOR LDA BIAS

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SUMMARY This paper examines three causes of error which may exist in measurements in flames and swirling flows, when seeding is used to obtain LDA- or concentration data. Differential diffusion between tracer and fuel is shown to cause bias in turbulent jet diffusion flames at moderate Reynolds number, when only the fuel stream is seeded. A theory to compensate for such bias is outlined. A magnitude estimate is presented for thermophoretic effects, which drive seed particles away from hot zones so that seed-free flow may occur in parts of the flame. The effect of centrifugation of tracer particles in swirling jets is discussed and seen to be proportional to the Reynolds number and to the square of the swirl number.

1 INTRODUCTION

Experimental work in the combustion laboratory at the University of Sydney on the turbulent hydrogen diffusion flame issuing into a co-flowing air stream has produced a data base which has become recognised as a benchmark for combustion modelling. Typically, only the fuel stream has been seeded, enabling simultaneous measurements of velocity and fuel element concentration by LDA and Mie scattering methods. In developing this technique, sources of error have been encountered which have not been given much attention in the literature. Differential diffusion between tracer and fuel has been found to distort measurements of scalars and velocity in low Reynolds number flames. Thermophoresis movement of tracer particles can be significant in the thermal, often laminar, layer near the nozzle. Finally, even at moderate levels of swirl, the centripetal acceleration of the seeded flow in the nozzle causes separation of particles, so that the tracer material becomes nonuniformly distributed at the nozzle exit plane.

In what follows, these difficulties are dealt with separately, and some experimental results are presented and compared with estimates of error magnitudes.

2 DIFFERENTIAL DIFFUSION EFFECTS

In turbulent flames of moderate jet Reynolds number, molecular diffusion makes a significant contribution to overall diffusion, i.e., for the gas species the turbulent diffusivity D_t is augmented by the molecular diffusivity D, whilst for the tracer material the 'molecular' diffusivity is negligible. Hence, differential diffusion between tracer and fuel arises.

The bias errors in measurements of scalars and velocity-scalar correlations by the Mie scattering technique, arising from differential diffusion of tracer and fuel, has been evaluated by Stårner and Bilger (1983) following the theory developed by Bilger (1980). A brief description of this approach follows here.

The tracer material is treated as an inert scalar, here denoted ξ_p, just like the fuel element mixture fraction ξ, except that ξ_p has zero 'molecular' diffusivity. Balance equations are written for the three quantities

$$\tilde{\xi}-\tilde{\xi}_p \; , \quad \widetilde{(\xi-\xi_p)''^2} \; , \quad \text{and}$$

$$\widetilde{(\xi+\xi_p)'' \, (\xi-\xi_p)''} \equiv (\widetilde{\xi''^2} - \widetilde{\xi_p''^2})/4 \; ,$$

where tilde overbars denote Favre averages. The usual boundary layer approximations are applied, gradient flux of ξ and ξ_p is assumed, and correlations between molecular diffusivities and scalar gradients are neglected. The three transport equations so formed are solved together with equations for $\tilde{\xi}$, $\widetilde{\xi''^2}$, momentum, turbulence kinetic energy and its dissipation rate. The computer code developed by Kent and Bilger (1977) is used. The gradient modelling for the additional equations is the same as for the k-ε model.

Table 1 shows computed results for a H_2 flame issuing at 151 m/s through a nozzle of diameter D = 7.62 mm into co-flowing air at 15.1 m/s with a mean axial pressure gradient of -18 Pa/m, and a jet Reynolds number of 10,850. Results are shown as fractional differences, with subscript o denoting centreline values. The radial coordinate is defined by $\eta = r/L$, where L is the radius at which the mean mixture

TABLE 1
Differential diffusion for a seeded H_2 flame

x/D	η	$\dfrac{\tilde{\xi}_p - \tilde{\xi}}{\tilde{\xi}_o}$	$\dfrac{(\widetilde{\xi_p''^2})^{1/2}-(\widetilde{\xi''^2})^{1/2}}{(\widetilde{\xi_o''^2})^{1/2}}$	$\dfrac{\widetilde{v''\xi_p''} - \widetilde{v''\xi''}}{\widetilde{v''\xi''}_{max}}$
40	0	0.068	0.077	
"	0.5	0.057	0.098	0.081
"	1.0	0.003	0.124	0.110
"	1.5	-0.034	0.021	0.005
80	0	0.109	0.150	
"	0.5	0.081	0.177	0.185
"	1.0	0.002	0.151	0.147
"	1.5	-0.026	-0.004	-0.008
120	0	0.122	0.197	
"	0.5	0.081	0.211	0.249
"	1.0	0.005	0.156	0.162
"	1.5	-0.023	0.012	-0.005
160	0	0.102	0.199	
"	0.5	0.055	0.190	0.240
"	1.0	0.010	0.116	0.100
"	1.5	-0.015	0.005	-0.004

fraction $\tilde{\xi}$ is half of its centreline value. The effect of differential diffusion on the mean mixture fraction ξ is modest, with a maximum error of 0.12 on the axis at x/D = 120. A small negative error occurs at the edge. Thus, the profile of $\tilde{\xi}$ is wider and lower than that of the tracer $\tilde{\xi}_p$, as expected, since ξ_p has lower diffusivity. The error in the rms of fluctuation, $(\widetilde{\xi''^2})^{1/2}$, rises to a maximum of 0.21 at x/D = 120. The effect on the radial velocity-scalar correlation $\widetilde{v''\xi''}$, the turbulent radial flux of ξ, has been computed by the use of gradient flux assumptions:

$$\widetilde{v''\xi''} - \widetilde{v''\xi''_p} = -\mathcal{D}_t\,\partial/\partial r(\tilde{\xi}-\tilde{\xi}_p) \quad . \tag{1}$$

The results in Table 1 show an error in $\widetilde{v''\xi''}$ rising with x/D to 0.25 at x/D = 120.

Stårner and Bilger (1983) show that magnitude estimates can be obtained from the simplified expressions

$$(\tilde{\xi}-\tilde{\xi}_p)_o \approx -\,2\tilde{\mathcal{D}}/(\mathcal{D}_t+\tilde{\mathcal{D}})\tilde{\xi}_o \tag{2}$$

and $$(\widetilde{\xi''^2}-\widetilde{\xi''^2_p})_o \approx -0.3\,\tilde{\mathcal{D}}/(\mathcal{D}_t+\tilde{\mathcal{D}})\tilde{\xi}^2_o \quad , \tag{3}$$

where $\tilde{\mathcal{D}}$ is the Favre averaged molecular diffusivity of the mixture fraction. It is also demonstrated that in the middle of the shear layer, the fractional error in $\widetilde{v''\xi''}$ is close to that of the rms of fluctuation of ξ, so that Eqn. (3) may be used also for $\widetilde{v''\xi''}$ error estimates. Eqns. (2) and (3) are considered to be generally applicable to any gaseous fuel, over the full Reynolds number range of turbulent jets. Bilger and Dibble (1982) note that for all three quantities modelled, there exists an inverse Reynolds number dependence, e.g., $(\tilde{\xi}-\tilde{\xi}_p)_o \propto \tilde{\mathcal{D}}/\tilde{\nu}\ \mathrm{Re}^{-1}$, where $\tilde{\nu}$ is the Favre averaged kinematic viscosity.

The influence of differential diffusion on mean velocity measurements in a densely seeded jet flow will be negligible near the centreline, but, as Table I shows, the jet will be insufficiently seeded near the edge, there causing bias of the mean towards higher velocity. To eliminate such bias, the external fluid must also be seeded, an option which is not open when simultaneous velocity and concentration data are wanted. For this case, the reader is referred to Stårner (1983), who has developed a bias compensation method, applied in the digital data reduction, which is based on weighting the velocity data by the probability density function of the simultaneously recorded concentration trace.

3 THERMOPHORESIS EFFECTS

In studying the upstream region of a nitrogen-diluted hydrogen diffusion flame, Masri et al. (1983) seeded both the jet and the co-flowing air stream to high and roughly equal density, to obtain unbiased LDA-data. Even so, the seeding density in the hottest region was found to be virtually zero. This cannot be attributed to differential diffusion, since, even if the fuel seeding is confined to the central region, the tracer concentration C (contributed by the air stream) near stoichiometric composition for this $2H_2/N_2$(v/v) flame is described by

$$C/C_e = [(1-\xi)\rho]_s/\rho_e \approx 0.07 \tag{4}$$

where ρ is the fluid density, and subscripts e and s denote external fluid and stoichiometric. This is quite adequate to yield good LDA-signal, yet the seeding level was negligible. It will be argued here that the cause is the thermophoretic diffusion of particles down the steep temperature gradients of the laminarized flame sheet which develops in the first few diameters downstream of the nozzle.

The seeding particles have a size range comparable to the mean free path of the gas in flames; this intermediate regime is difficult to put on a sound theoretical footing. However, for the case where the particle thermal conductivity λ_p is much larger than that of the gas, λ, the theory of Deryagin and Yalamov, quoted by Waldmann and Schmitt (1966) reduces to a simple expression for the thermophoretic velocity v_p of the particles, relative to the fluid:

$$v_p \approx -\frac{2}{3}\frac{\lambda}{5p}\ \text{grad}\ T \tag{5}$$

where p is the gas pressure and T its temperature at some distance from the particle. Measurements by Schmitt on silicone oil drops ($\lambda_p/\lambda = 7.5$), as reviewed by Waldmann and Schmitt,(1966) agree satisfactorily with Eqn. (5). Schefer et al. (1979) studied the thermophoresis of 2 µm $A\ell_2O_3$ particles in the thermal boundary layer over a heated plate. The experimental thermophoretic velocities are reported as 25 times their predictions, which are based on the form

$$v_p = -\frac{2\lambda}{2\lambda+\lambda_p}\,\sigma\,\frac{\lambda}{p}\ \text{grad}\ T \quad . \tag{6}$$

This is essentially the Epstein equation, which is known to yield too low v_p for large λ_p/λ. In Eqn. (6), σ is the thermal slip factor, usually taken as 1/5. If, instead, Eqn. (5) were used for the calculation (assuming λ_p = 6.5 W/m,K, based on material bulk properties, and a typical gas temperature of 1000K) the predicted v_p would be 33.3 times larger, thus agreeing quite well with the experiments.

The foregoing enables us to apply Eqn. (5) with some confidence to an estimate of the thermophoresis in the flame of Masri et al. We consider the thermal layer in the wake of the nozzle lip: with typical values of λ and grad T of 0.1 W/m,K and 5 x 10^5 K/m, Eqn. (5) yields v_p = 0.1 m/s. The mean streamwise velocity in the wake of the lip for the first five diameters is of order 5 m/s, so a particle leaving the nozzle lip would move radially about one mm, and we would expect a seed-free zone about 2 mm wide at x/D = 5. Experimentally, the width is found to be around 4 mm, indicating that this estimate is of the right order, though it seems somewhat conservative.

The problem pertains to 'slow' flames with laminar or laminarized regions and cannot be easily overcome, as Eqn. (5) indicates independence of both particle size and material properties. If the flame undulates, gross LDA-bias will obviously occur near the hottest region, which will simply not be sampled, being seed-free. Once turbulence is fully developed, the thermophoretic effect will obviously become negligible.

4 CENTRIFUGATION OF SEEDING IN SWIRLING FLOWS

Work is now under way to extend the data base for the hydrogen flame mentioned in Section 1, to include also the effects of moderate swirl. Admixture of nitrogen to the fuel stream has been found useful to raise the Reynolds number so that differential diffusion effects are suppressed.

Originally, a moving vane swirl generator of the Ijmuiden type was fitted to the fuel pipe 300 mm from the nozzle exit plane, upstream of a 10:1 smooth contraction ending in a sharp-edged nozzle of 20.24 mm diameter. It was immediately found that even for a low swirl number, S = 0.4, the seeding particles ($A\ell_2O_3$, nominally 0.3 µm) emerged from the nozzle badly distributed; the number density near the nozzle lip was almost 10 times that on the axis (as measured by laser light scattered off the particles). A 40 mm long swirl generator with three fixed axial vanes, producing S = 0.3, was substituted, and fitted just inside the nozzle, thus reducing the axial distance over which the centrifugation would act.

Figure 1 shows measurements of the resulting seeding distribution for MgO powder, and a TiO_2 aerosol produced by reacting $TiC\ell_4$ with H_2O vapour in the fuel stream.

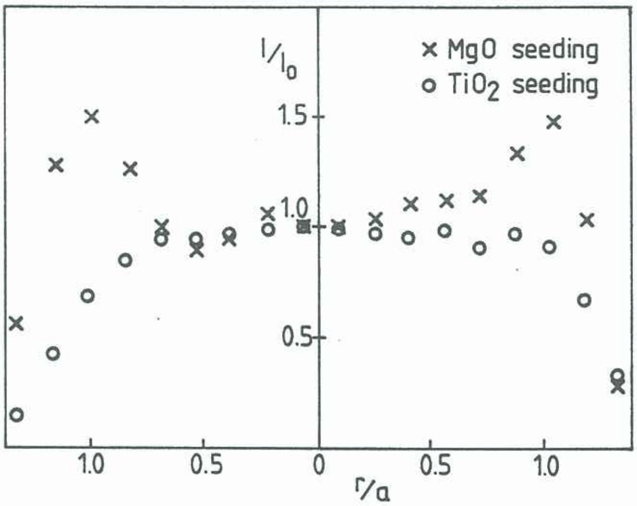

FIG. 1. Radial profiles of scattered light intensity I for TiO_2 and MgO seeding. Re = 26,000; S = 0.3; x/D = 0.6

The MgO powder (nominal particle diameter d_p only 0.02 µm) was dispersed by a reverse cyclone seeder, resulting in polydisperse agglomerates with estimated mean size of 2 µm. The TiO_2 aerosol has a narrow size range of 0.1-0.5 µm. It is seen that the MgO powder distribution has peaks near the nozzle wall some 50 percent above the centreline value, a much more even result than with the Ijmuiden generator, but still not acceptable for concentration measurements. The TiO_2 profile, on the other hand, shows no centrifugation effect. However, Kennedy (1979) has documented that TiO_2 is optically unstable in pure H_2 flames, and an experiment performed during the present investigation with the 50 percent N_2-diluted fuel (400 K cooler than for pure H_2) confirms his findings; a loss in scattered light intensity of about 50 percent occurs as the particles enter the stoichiometric region, compared with $A\ell_2O_3$ seeding, which has been shown (Kennedy 1979) to be stable. This makes the TiO_2 aerosol produced by this method unsuitable for concentration measurements.

It is useful to attempt a theoretical estimate of the centrifugation effect. In the steady state, we can equate centripetal acceleration with the Stokes drag force to obtain

$$v_p = \frac{1}{18\mu} d_p^2 \rho_p \frac{w^2}{r} \qquad (7)$$

where w is the tangential gas velocity and µ the absolute fluid viscosity. We assume uniform streamwise velocity u across the nozzle and solid body rotation in the nozzle, i.e., $w(r) = w_{max}\, r/a$, where a is the nozzle radius. The swirl number, defined in the usual way, then reduces, for moderate swirl, to $S \approx w_{max}/(2u)$.

By insertion of S and the jet Reynolds number into Eqn. (7), we obtain the radial deviation angle θ of a particle from the axial direction, near the nozzle lip:

$$\theta = \tan^{-1}\left(\frac{v}{u}\right) = \tan^{-1}\left\{\mathrm{Re}\, S^2 \frac{\rho_p}{9\rho} \frac{d_p}{a^2}\right\} \qquad (8)$$

In the case of Fig. 1, for MgO seeding (taking d_p = 2 µm and bulk material properties) θ = 0.89°, and for TiO_2 (d_p = 0.3 µm) θ = 0.020°. With a 40 mm approach length of the swirling flow to the nozzle exit, an MgO particle would then move 0.62 mm radially and a TiO_2 particle 0.014 mm. The result in Fig. 1 for TiO_2 obviously does not conflict with this estimate; there is no appreciable centrifugation effect. The estimate for MgO, 0.62 mm, should be detectable, though probably not as large as in Fig. 1, indicating that real particles may be larger than the assumed 2 µm. It should also be considered that large particles, which are strongly centrifugated, are also strong scatterers (light intensity $I \propto d_p^6$ in the Rayleigh regime, $I \propto d_p^2$ for large particles). This circumstance would tend to increase the uneven light intensity distribution seen in Fig. 1 for MgO, and would also lead to increased marker shot noise towards the edge of the jet.

It is clear that centrifugation effects are best minimized by close attention to the choice of tracer material and the method used for its dispersion. Particle diameters as small as 0.1 µm can yield adequate LDA signal, but dispersion by mechanical or aerodynamic (e.g. cyclone) means is likely to result in much larger agglomerates. The author's efforts to minimize electrostatic effects, and to improve the fluidity of seeding powders, by using mixtures of MgO, $A\ell_2O_3$ and silica, have not led to significant improvement. A rather sophisticated spark discharge seeding system for dispersing dry powders, developed by Altgeld (1979), is reported to yield a mean particle size of 0.1 µm with a standard deviation of 0.3 µm.

5 CONCLUSIONS

Quantitative estimates have been presented for a selection of error sources which may arise in dealing with Mie scattering and LDA measurements in seeded flows. To minimize the effects of differential diffusion and thermophoretic movement of tracer particles in diffusion flames, the jet Reynolds number should be maximized, and the nozzle design and experimental conditions such that the regions of laminarized flow are minimized. In swirling flows, to reduce nonuniformity of seeding due to centrifugation, the particles should be small and light, and have a narrow size range. Also, the swirl and Reynolds numbers should be as low as is consistent with the experimental objectives.

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