Combustor Swirl Flow Modeling

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Theme

A CHALLENGING problem facing theoretical combustion aerodynamicists today is the prediction of turbulent reacting swirl flows. Prediction greatly facilitates economical design and operation of combustion systems, where flame size, shape, stability, and combustion intensity are often controlled by the use of, among other things, swirl.[1] The degree of swirl is characterized by the swirl number S (axial flux of angular momentum divided by the axial flux of axial momentum times nozzle radius), or the local swirl number S_z (which uses the local mixing layer width). The swirl strength determines the degree of upstream influence. The flow classification of parabolic (boundary-layer type with a single predominant direction—weak swirl $S < 0.4$) or elliptic (recirculating type with upstream influence—strong swirl $S > 0.6$), governs the type of boundary conditions required and the solution method. Marching methods are appropriate for the former; relaxation methods for the latter.[2] Recent work in the simulation and solution of these flows is reviewed in Ref. 3 and the full-length paper.

Contents

Mathematical Models

The turbulent flux (Reynolds) equations of conservation of mass, momentum, stagnation enthalpy, and chemical species, which govern the flow of turbulent chemically-reacting multi-component mixtures, may be solved for time-mean pressure, velocity, temperature, and specie mass fractions, provided the further thermodynamic and turbulent flux unknowns are specified prior to solution. Often, consideration is given to a simplified main exothermic reaction between just two species, fuel and oxidant; this and other assumptions leads to many simplifications. The reaction is then characterized by equations for 1) m_{fu} (mass fraction of fuel), h (stagnation enthalpy), and f (mixture fraction $m_{ox} - im_{fu}$ where i is the stoichiometric ratio) for a premixed flame; 2) h and f for a diffusion flame; or 3) f for a diffusion flame in an adiabatic, nonreacting, and impervious chamber with only two inlet streams of fuel and oxidant. Solution for a variable g (mean square fluctuating component of fuel concentration) allows a turbulent diffusion flame to have a thick reaction zone or a premixed flame to burn fuel at a rate dependent on eddy-break-up concepts. The turbulent fluxes must be specified via a turbulence model, often, by analogy with the laws of Newton, Fourier, and Fick for laminar flows, using turbulent exchange coefficients relating fluxes to local gradients and then Prandtl, Schmidt, and $r\theta$- (and other-) viscosity numbers relating other exchange coefficients to the primary component of turbulent viscosity μ.

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Reactive Flows; Combustion in Gases.

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Computational Procedures

Standard computer programs are available for the prediction of 2-D boundary-layer[4] and recirculating flows, using the primitive pressure-velocity[5] or stream function-vorticity[6] approach for the latter, and both these have been modified to predict swirling reacting flows. For 3-D flows, methods are also available.

Modeling of the Processes

For the simulation of turbulence, modifications to standard exchange coefficient-type models are recommended for weakly swirling parabolic flows in the form

$$\lambda = 0.08(1 + \lambda_s S_z) \qquad \lambda_s = \text{constant} = 0.6 \tag{1}$$

for an extended algebraic mixing length model $\mu = \rho l^2(2\Delta:\Delta)$, where λ is mixing length parameter, l is mixing length, ρ is local time-mean density, and Δ is the mean-flow rate of strain tensor (this degenerates into the standard Prandtl model with $\lambda = 0.08$ in the case of a nonswirling flow with boundary layer assumptions), and

$$\text{additional source term in } kl \text{ equation} = C_R \rho\, Ri\, k^{1.5} \tag{2}$$

for the two-equation $k-kl$ energy-length model $\mu = \rho k^{1/2} l$ (where two differential equations are solved to obtain the two turbulence parameters k and l), where C_R is a constant = 0.06, Ri is the Richardson number, and k and l are the kinetic energy and length scale of turbulence. Strongly swirling enclosed flow, for example reacting flow in an assumed axisymmetric cylindrical combustion chamber (where in any case laterally induced secondary air creates extra turbulence), may be well predicted on the basis of a simple algebraic turbulence model which uses initial velocities and mass flow rates to give approximate turbulent jet values of μ near the inlets

$$\mu = K(D^2\rho^2[\dot{m}_P u_P{}^2 + \dot{m}_S(u_S{}^2 + w_S{}^2)]/L)^{1/3} \tag{3}$$

where K is a constant = 0.012, D and L are diameter and length of chamber, $\dot{m}_P$ and $\dot{m}_S$ are mass flow rates, and u_P and u_S are inlet axial velocities of primary and surrounding annular secondary streams, and w_S is the inlet swirl velocity of the secondary stream. Nonisotropy is obtained by using ad hoc nonunity values of $r\theta$- (in particular) and other-viscosity numbers. For the simulation of the combustion process, an expression for the consumption rate of fuel R_{fu} must be incorporated only if the reaction is premixed—the time-averaged Arrhenius and eddy-break-up models being considered (the latter being recommended as a promising new model)[7]

$$R_{fu} = -Pp^2 m_{fu} m_{ox} \exp(-E/RT) \tag{4}$$

and

$$R_{fu} = -C_{EBU}\, \rho g^{1/2} k^{1/2}/l \tag{5}$$

where $P = 0.5$, $E/R = 20{,}000$, and $C_{EBU} = 0.53$ are constants, p is time-mean pressure, and m_{fu} and m_{ox} are time-mean mass fractions of fuel and oxidant.

Computations

Predictions of weakly swirling jets with either turbulence model Eq. (1) or (2), and nonisotropy obtained from $\sigma_{r\theta} = 1 + CS_z{}^{1/3}$ where $\sigma_{r\theta}$ is the $r\theta$-viscosity number and C is a parameter taking a value between 2 and 5, show good agreement with experiment for jet growth, entrainment, and decay. Weakly

swirling premixed jet flames are also predicted with either turbulence model and the eddy-break-up reaction model, Eq. (5). Flame size, shape, and combustion intensity are strongly affected by swirl and compare favorably with experimental data. Downstream development of these flows is often characterized by the parameters A (for axial velocity decay) and α (for jet half-angle) defined by

$$u_m/u_{mo} = A(\rho_\infty/\rho_{\min})^{1/2}d/(z+a) \quad (6)$$

$$\tan\alpha = r_{0.5}/(z+a) \quad (7)$$

where u_m is station maximum time-mean axial velocity, u_{mo} is its value initially at nozzle exit, ρ_∞ and $\rho_{\min}$ are ambient and station-minimum time-mean densities, d is nozzle diameter, z is downstream distance, a is apparent origin distance upstream from nozzle, and $r_{0.5}$ is the radial distance from axis to $u/u_m = 0.5$. Recommendations for a, A, α, and flame lengths are given in Table 1.

Table 1 Development parameters for jets and premixed ($m_{fu} = 0.245$) jet flames

	Jet ($S < 0.4$)	Flame ($S < 0.23$)
a/d	2.3	$35+100S$
A	$6.8/(1+6.8S^2)$	$15+10S$
α	$4.8+14S$	$2.2+S$
Flame length/d	...	$43-100S$

Strongly swirling enclosed and free jets, generated via the use of swirl vanes or a swirl generator, are well-predicted on the basis of Eq. (3). Results for the length of central recirculation zone, axial distance to impingement, and velocity decays are encouraging and discussed fully in the full-length paper. Here emphasis is placed solely on the more practical flow considered: the flow in a cylindrical combustion chamber. Figure 1 illustrates a computation for the combustor, which has many of the features of practical equipment: fuel gas and air input at one end, exit for combustion products at the other; arrangement for the air inlet as an annular orifice (outer diameter $d = 0.0762$ m) surrounding the fuel inlet; swirl vanes for causing the air to enter with a swirling motion (w constant profile); and a thick annular lip between the air and fuel inlets, its thickness so chosen that equal axial velocities of the primary fuel stream u_P and the secondary airstream u_S give over-all stoichiometric conditions (air-fuel ratio AFR = 15). For simplicity, a diffusion flame is assumed and the turbulent viscosity formula Eq. (3) is used. Results were not found to be very sensitive to any ad hoc non-isotropic tests. It needs to be stressed that more satisfactory turbulence and reaction models now exist; the predictions shown are intended as demonstrative, and as such, the following conditions are taken at the inlet: $p = 25$ atm, $T = 850$°K and $u_S = 36$ m/s. The exit boundary is taken to be parallel flow at $z/d = 8$.

Figure 1 shows the predicted streamlines and flame envelope for a swirl vane angle ϕ of 60° and primary fuel velocity u_P of 18 m/s ($= 0.5u_S$), giving an inlet AFR of 30:1. Notice that the presence of this degree of swirl ($S \simeq 1.1$) causes a toroidal vortex

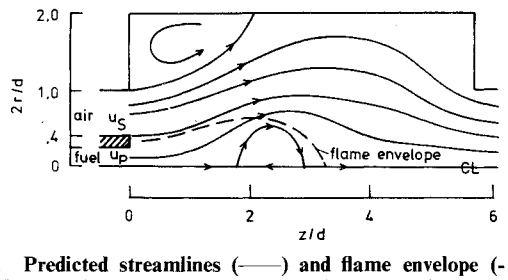

Fig. 1 Predicted streamlines (——) and flame envelope (---) in a combustion chamber (vane angle 60°, primary velocity $u_P = 0.5u_S$).

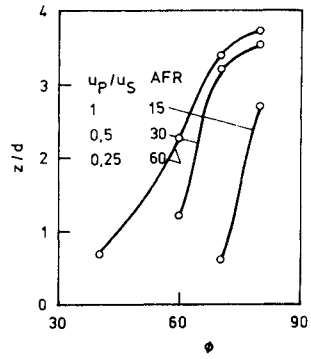

Fig. 2 Effect of swirl vane angle on central recirculating zone length for reacting flow in combustion chamber (*o* pred.).

to form in the middle of the combustion chamber, in addition to the corner recirculation near the entrance provoked by the sudden enlargement of the cross-sectional area. It has also shortened the flame, as compared with a nonswirling case, but still the flame engulfs the central recirculation zone. Both these effects are well-known to combustion engineers who strive to utilize the recirculation of hot combustion products and the bluff body effect of this zone as an aid to the combustion process.

The vane angle has a strong effect on the existence (or otherwise) and size of the central recirculation zone. Shown in Fig. 2 is the length of this zone as a function of vane angle for a variety of values of u_P (and hence AFR). The zone lengthens as ϕ increases for a given u_P (AFR). Reduction of u_P promotes the existence of the zone and lengthens it for a given vane angle. A third point is that with chemical reaction suppressed the zones are found to be longer; the presence of reaction, gas expansion and increased velocity tends to shorten, and in some cases destroy, the zone as compared with its nonreacting counterpart.

Predicted also, and as expected experimentally, reduction of u_P (increase in AFR) and/or increase in vane angle progressively reduces the flame length and improves the temperature traverse quality (uniformity of temperature) across the exit from the combustor.

General Observations

The presence and increase in size of a central recirculation zone is encouraged by increasing D/d, having a central hub in the inlet flow $d_h > 0$, increasing d_h/d, reducing primary velocity (also shifts zone more upstream), increasing swirl number or swirl vane angle, and suppressing chemical reaction. Work is in progress at Cranfield on the development of a general recirculating flow computer program which solves axisymmetric swirling flows in terms of the primitive variables and includes solution of additional equations for k and ε (turbulence), g (turbulent diffusion flame), and others for eddy-break-up premixed reaction and the presence of a fuel droplet spray.

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