Swirl Flows in Combustion: A Review

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I. Introduction

RECENTLY, concentrated research effort has been expended on understanding and characterizing the combustion aerodynamics of swirl flow burning processes of gaseous, liquid, and solid fuels. Economical design and operation of practical combustion equipment can be facilitated greatly by estimates made from complementary experimentation and modeling studies. Such work combines experimental and theoretical combustion aerodynamics with sophisticated computational fluid dynamics and its improvement and use will reduce the cost of development programs significantly. Detailed surveys of these studies are to be found in the literature.[1-11]

Swirling flows result from the application of a spiraling motion, with a swirl velocity component (also known as a tangential or azimuthal velocity component) being imparted to the flow via the use of swirl vanes, in axial-plus-tangential entry swirl generator or direct tangential entry into the combustion chamber. Experimental studies show that swirl has large-scale effects on flowfields: jet growth, entrainment, and decay (for inert jets) and flame size, shape, stability, and combustion intensity (for reacting flows) are affected by the degree of swirl imparted to the flow. This degree of swirl usually is characterized by the swirl number S, which is a nondimensional number representing axial flux of swirl momentum divided by axial flux of axial momentum times equivalent nozzle radius. In this context, for comparison purposes it is worth noting that swirl vane angle ϕ and swirl number S are related approximately by

$$S=\frac{2}{3}\left[\frac{1-(d_h/d)^3}{1-(d_h/d)^2}\right]\tan\phi\approx\frac{2}{3}\tan\phi \qquad (1)$$

for $d_h \ll d$, so that vane angles of 15, 30, 45, 60, 70, and 80, for example, correspond to S values of approximately 0.2, 0.4, 0.7, 1.2, 2.0, and 4.0. Here 100% efficiency also is assumed for the swirl vanes, which deteriorates as the vane angle increases.

The effect of a low degree of swirl (weak swirl, $S< \sim 0.4$) is to increase the width of a free or confined jet flow: jet growth, entrainment, and decay are enhanced progressively as the degree of swirl is increased. At higher degrees of swirl (strong swirl, $S> \sim 0.6$), strong radial and axial pressure gradients are set up near the nozzle exit, resulting in axial recirculation in the form of a central toroidal recirculation zone, which is not observed at weaker degrees of swirl. In particular, swirl is used extensively as an aid to efficient clean combustion in a variety of practical situations: gasoline engine, diesel engine, gas turbine (including central toroidal recirculation zone), industrial furnace, utility boiler, and many other practical heating devices, including small domestic home furnaces. Recent interest also is being shown in rotary (Wankel) and stratified charge engines in our desire for efficiency and cleanliness. In design situations, the engineer has to seek an optimum path between irreconcilable alternatives of, for example, efficiency and pollution.[12-15]

Consideration is given to the major features of the characterization of swirl flow combustion, with emphasis on application to practical combustors. Recent experimental work is surveyed in Sec. II, with special regard to the main effects of swirl on the performance, stability, and combustion intensity of flames in combustors. Since solution of the basic governing equations yields predictions that are realistic only if the physical processes are sufficiently well expressed in mathematical form and suitable computational methods of solution are employed, these details are discussed in Sec. III. The treatment is brief, since extensive reviews are available in the literature. It is possible to predict major features of these swirling flows; some solutions are exhibited in Sec. IV. The Closure summarizes the achievements and current status.

II. Experimental Work

Almost all industrial flames have the form of turbulent jets issuing from round orifice burners. Sometimes the fuel gas is introduced through a central jet (maybe premixed) and the remaining air through an annulus surrounding it, so that double concentric jets are formed. If the fuel enters as liquid droplets or coal particles, it is either atomized or sprayed from the central region, again with a surrounding annulus of air. Either the primary or the secondary (or both) is given a certain degree of swirl to enhance the jet and flame characteristics. Tangentially fired equipment differs from wall-fired

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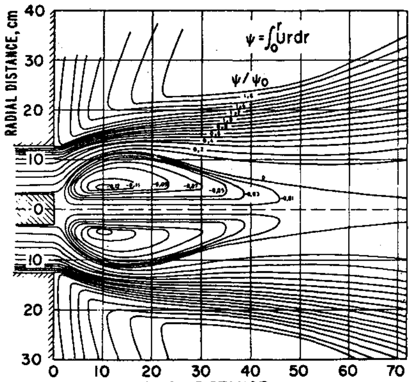


Fig. 1 Streamlines in swirling annular freejet; $S=1.57$ (Ref. 16).

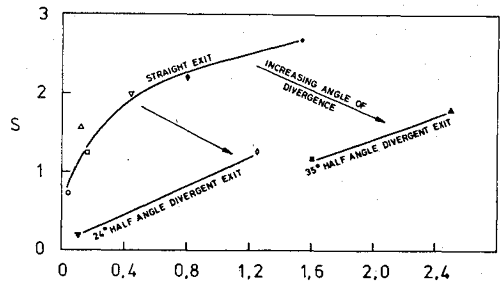


Fig. 2 Variation of recirculated mass flow in freejets with swirl number.[5]

equipment in that no swirl is imparted to the incoming streams, but these streams are directed so as to aim tangentially at the fireball that results in the center. These swirl effects, documented at length in Refs. 1-70, now are discussed.

A. Swirling Flows

Extensive studies of the effect of swirl on jet flows have been made and reported elsewhere,[1-4] for both single and double concentric nozzle flows, free and confined. As an introduction to this literature, some of the salient features now are discussed. General effects of introducing swirl on turbulent jets are to cause an increase in width, rate of entrainment, and rate of decay in the jets as the degree of swirl is increased progressively. Pressure fields are induced to balance centrifugal forces, and the decay of swirl caused by shear and mixing with surrounding fluid sets up adverse axial pressure gradients. The form of the radial distribution of time-mean axial velocity depends on the degree of swirl S imparted to the flow. For weak swirl, the distribution remains Gaussian in form, with the maximum velocity on the axis of the jet. As the swirl number is increased, the radial spread of the jet increases, and, for jets with swirl greater than a certain critical swirl number (approximately $S=0.6$), the forces due to the axial adverse pressure gradient exceed the forward kinetic forces and the flow reverses its direction in the central region of the jet, in the vicinity of the nozzle. At $S=0.64$, the length of the reverse flow region is 4 jet diameters.

For combustion applications, one of the most significant and useful phenomena of swirling jet flows is the recirculation bubble generated centrally for supercritical swirl numbers. From the point of view of long-time mean averages, boundaries of the recirculation bubble and reverse flow zones are well defined. The flows generally are associated with high rates of shear and values of turbulence intensity so that instantaneously large-scale spatial fluctuations of boundaries and stagnation points occur. Streamlines calculated from measured time-mean velocity distributions are shown for a swirling annular freejet (issuing from a swirl generator) with $S=1.57$ in Fig. 1.[16] The recirculation bubble plays an important role in flame stabilization by providing a hot flow of recirculated combustion products and a reduced velocity region where flame speed and flow velocity can be matched. Flame lengths and distance from the burner at which the flame is stabilized are shortened significantly.

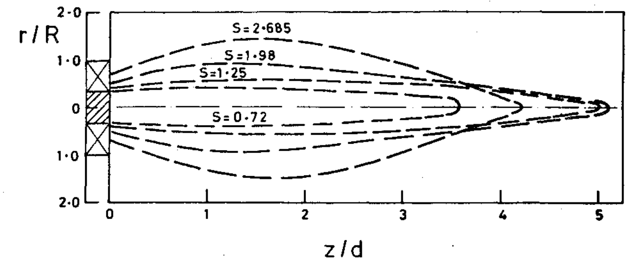


Fig. 3 Size and shape of reverse flow zone in freejets from annular vane swirlers with straight exits.[5,20]

Of course, the precise effect of swirl on a flowfield is found to depend on many factors as well as the swirl number: for example, nozzle geometry (the presence of a central hub encourages a larger recirculation zone, as does the addition of a divergent nozzle), size of enclosure if any (central recirculation zones are much more pronounced in enclosures than those of comparable freejets), and the particular exit velocity profiles (recirculation zones tend to the larger when the flow is produced via swirl vanes as opposed to an axial-and-tangential entry swirl generator).

Turbulence intensity reaches very high levels in recirculation bubbles. On the reverse flow boundary, where the mean velocity is zero, the local turbulence intensity tends to infinity. Measurements of all six different turbulent stress components show strong variations of absolute turbulence kinetic energy levels and strong nonisotropy of the stresses and associated turbulent viscosity.[17] The exchange coefficients are found to be functions of the degree of swirl and position in the flowfield, as can be shown also by analytical and numerical inverse solution procedures applied to the simpler situation of weakly swirling jets and flames.[18,19]

The size and shape of the recirculation zone and associated region of high turbulence are critical to flame stability, combustion intensity, and performance. Regardless of the type of swirl generator (apart from hubless vane swirlers), the "eye" of the recircualtion eddy always occurs very close to the nozzle exit, and streamline patterns similar to those of Fig. 1 also result. The main differences lie in the recirculated mass flow produced, and Fig. 2 shows that there is good correlation between the swirl number S and recirculated mass flow M_R/M_0 for free swirling jets.[4] Here the suffices R and 0 stand for reverse and initial values. The presence of an oil gun at the throat of a swirl generator appears to halve M_R/M_0; the presence of a divergent outlet has a disproportionately large effect of greatly increased M_R/M_0 for a given swirl number. Although the point of onset of reversed flow generally is taken to occur at approximately $S=0.6$, it is clear that divergent exit nozzles substantially reduce this requirement.[5]

The size and shape of the reverse flow zone depend principally on the degree of swirl, as shown in Fig. 3, and angle of divergence of the outlet. The figure shows the effect of swirl for annular vane swirlers with straight exits.[5,20] The trends, even though there are experimental difficulties in taking measurements in regions of low velocity, are evident. As the swirl number (associated with vane angle) is increased, the narrow recirculation zone becomes longer, reaching a maximum at about $S=1.5$, and subsequently becomes shorter and wider at $S>2$. Recirculation zones produced by swirl generators (that is, axial-plus-tangential entry swirl generators) generally are much smaller than those produced by swirl vanes, for a given swirl number. Since mass flow rates at similar swirl numbers are similar, it is clear that higher reverse flow velocities, higher velocity gradients, higher turbulence levels, and higher rates of mixing are associated with the much more compact reverse flow zone from the swirl generator.

B. Swirling Flames

The length of nonswirling fully developed turbulent diffusion flames is unaffected by an increase in velocity through a given burner, in contrast to laminar flames, and in free surroundings is dependent mainly on the type of fuel used and the diameter of the orifice. If the flame is confined in an enclosed furnace, the flame length increases, owing to the lack of entrainment of oxidant and the presence of recirculation, by about 25%, but this depends on the oxygen concentration of the recirculation gases and degree of confinement D/d, where D and d are enclosure and nozzle diameters. Partially premixed flames are shorter, and the intensity of combustion is greater, this depending on the degree of premixing.

Phenomena similar to those observed and measured in nonreacting swirling flows have been observed and measured in swirling flames. The recirculation bubble plays an important role in flame stabilization by providing a heat source of recirculated combustion products and a reduced velocity region where flame speed and flow velocity can be matched. Flame lengths and the distance from the burner at which the flame is stabilized are shortened significantly. Direct comparisons of turbulent flowfields in nonreacting media with those in flames show that the thermal molecular and atomic energy changes in the flames induce comparatively small changes in the gasdynamic flowfields of recirculating swirling jets. Reverse flow boundaries and reverse mass flow rates are reduced only slightly with combustion.[21]

With swirl, the axial velocity radial profile exhibits off-centerline maxima at a short distance downstream of the nozzle (exhibiting reverse flow close to nozzle), as measured typically in an industrial furnace. The high-temperature zone fo the flame front is deflected from an annular position for the fuel jet without swirl to a jet centerline position for the case with swirl. This is due to the increased mixing and reaction rates in the swirling flame. The effect of increasing swirl number on the flame front (maximum temperature) lines in free nonrecirculating flames is shown in Fig. 4, where $R = 0/2$ is nozzle radius.[6] Further details about the effect of combustion on reverse flow boundaries, including the effect of mixture ratio, type of fuel entry, etc., may be found in Refs. 1-6.

The reverse flow zone of a recirculation bubble has many of the characteristics of a well-stirred reactor in that the temperature and gas composition within the reverse flow zone are almost uniform. This well-stirred zone is fluid-dynamically confined and surrounded by nonreacting room-temperature air. The levels of temperature and gas composition can be controlled by the amount and nature of the fuel injected into the zone, and aerodynamic control is achieved by varying the degree of swirl. A means thus is available for controlling the rates of formation and reaction of carbon and oxides of nitrogen, and thus, for any particular flame, optimum conditions can be found for minimum net production of carbon and nitrogen.

Premixed vane swirled flames in furnaces with expansion ratios $D/d = 2.5$ and 5.0 have been studied at Glasgow from the aerodynamic and modeling points of view.[22] It is found that the same swirler can give different velocity patterns as the relative furnace size D is changed, and the size and shape of the central recirculation zone, if present, are primarly functions of D and not of d. Correlations between flow types A, B, C, and D and the modified swirl number

$$S^* = Sd/D \tag{2}$$

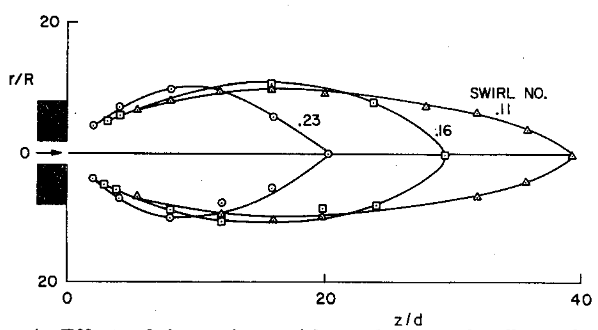


Fig. 4 Effect of increasing swirl number on the flame front (maximum temperature) lines in free nonrecirculating swirling flames.[6]

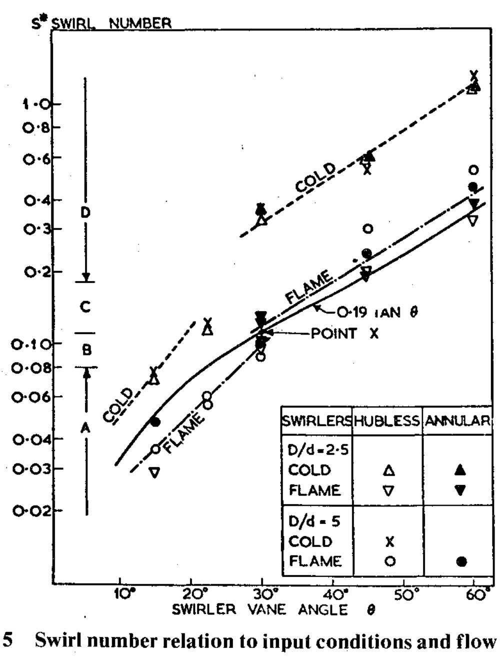


Fig. 5 Swirl number relation to input conditions and flow type.

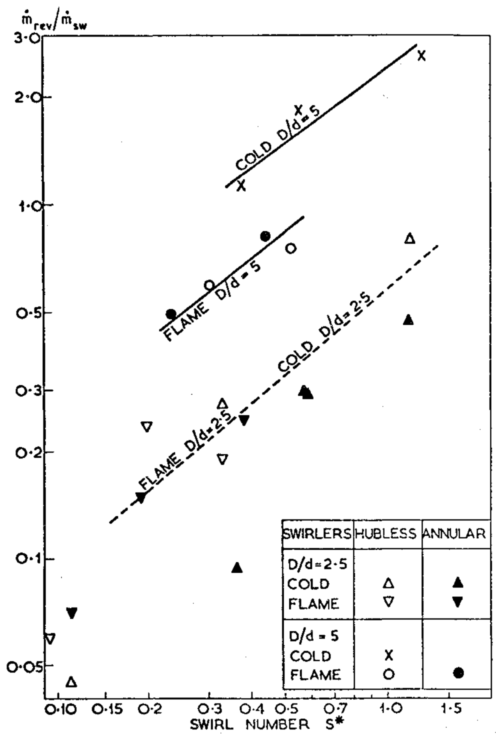


Fig. 6 Variation of reverse mass flow in central recirculation zone with swirl number S^* (Ref. 22).

based on furnace radius instead of nozzle radius are very satisfactory and are shown in Fig. 5. The flow types considered are as follows: A, very weak swirl and no significant through in velocity on the axis; B, through in velocity on the axis but no reverse flow; C, weak reverse flow; and D, strongly established central recirculation zone. Transition between these types occurs at values of S^* of 0.08, 0.11, and 0.18. Furthermore, for a given swirler and a given air-fuel ratio (isothermal or burning flow), the S^* values are very similar in the two relative furnace sizes. There is a change in the slopes of both the isothermal and burning characteristics at a vane angle of about 30°, corresponding in the burning case to the transition to the formation of a central recirculation zone. Figure 6 shows the corresponding reverse mass flow in the central recirculation zone as a function of S^*, cold or flame conditions, with an expansion ratio $D/d = 2.5$ and 5.0.

Recent laser anemometer measurements in free swirling flow under flame and no-flame conditions have been reported.[23] These include measurements of velocity and turbulent kinetic energy, and they show that substantial increases are found in turbulent kinetic energy and velocity fluctuations as a consequence of combustion.

The effect of swirl on flame length is demonstrated both experimentally and theoretically using simple models for a turbulent diffusion flame in a cylindrical furnace.[24] Here swirl is imparted only to the annular flow of air, surrounding the central fuel nozzle, and inlet conditions are stoichiometric. The trends resemble those for the free premixed flames of Fig. 4.

Stability, mixing, and interaction of multijet natural-gas flames with swirl have been investigated experimentally.[25] The effect of burner crowding and separation on the flame length, for different values of S, shown in Fig. 7, is representative of the results obtained. It is clear that flame length increases with increased number of burners, greater proximity, and lower degree of swirl. The presence of another flame in the near vicinity of a flame decreases the surface area that is in direct contact with the atmosphere, so that entrainment is hindered. Also, the influence of burner crowding is found to be even more pronounced in fuel-rich flames because in these cases only small changes in the amounts of air entrained strongly affect the combustion processes. Blow-off limits of the multiple burner systems are shifted toward the fuel-rich region. For conditions approaching the critical blow-off, a central flame could be lifted or blown off the burner while the surrounding flames remain attached to their burners.

The effect of swirl on residence time distribution and the performance and efficiency of combustors are determined experimentally in Ref. 26. A comparison of tracer concentration decay curves obtained for a water model and a pulverized fuel furnace for varying degrees of swirl is shown in Fig. 8. The ability to vary the ratio of mean residence time in the perfectly stirred and plug-flow sections of the combustor, by varying the degree of inlet swirl, is of great significance in design. A similar investigation on the stability and combustion intensity of pulverized-coal flames discusses the effect of swirl and impingement of the secondary annular air supply.[27] Important results are that secondary air swirl leads to a pronounced improvement in the stability of flames and leads to a reduction in the distance between burner and flame front.

Most complete laser anemometer measurements of swirling flow under confined conditions, with and without combustion, are available recently.[28] These were obtained in the Imperial College, London, and Harwell furnaces. As an example, Fig. 9 shows contours of constant velocity for two sets of results, representing isothermal flow and combusting flow. Each set is obtained at two levels of swirl, in an axisymmetric furnace, using a combustible mixture of air and natural gas. The boundary and field measurements of three components of time-mean velocity and corresponding normal stresses were designed to be of good use in the evaluation of turbulent flow prediction procedures and thus, to this end, necessarily are far more detailed and accurate than previous studies in the Delft, Ijmuiden, and Karlsruhe furnaces. Results demonstrate, for example, that the regions of recirculation under the reacting flow conditions differ substantially from those under nonreacting conditions. The turbulence is found to be far from isotropic over most of the flowfield. It also is clear that, as a consequence of the combustion, the velocity fluctuations increase significantly when appropriate integrals over the entire flowfield are performed, thus supporting, in some sense, the hypothesis of combustion-generated turbulence.

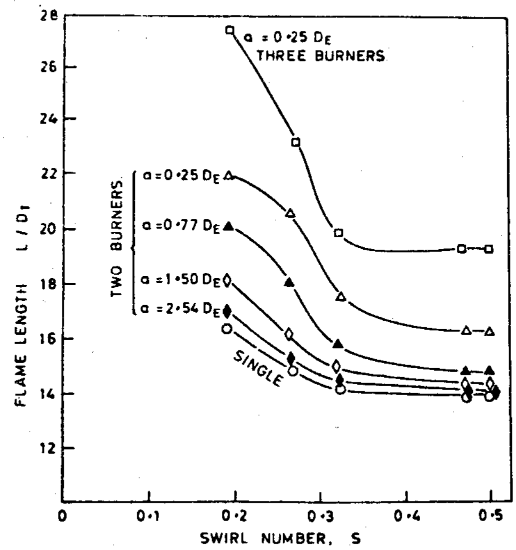
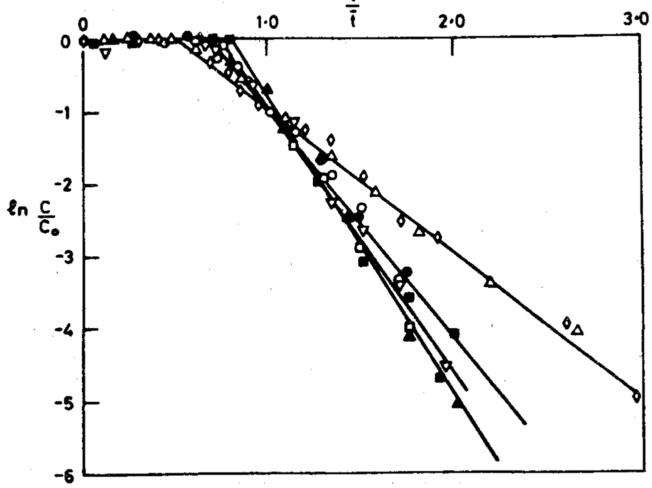


Fig. 7 Effect of burner crowding and separation on flame length.[25]



	$G_\phi / G_x R$		$\bar{t}$ sec
◊	0	FURNACE	15·2
△	0	MODEL	20
■	1·56	FURNACE	18·3
▲	1·56	MODEL	20
□	2·24	FURNACE	17·9
▽	2·24	MODEL	20
○	3·9	FURNACE	19·3
●	3·9	MODEL	20

Fig. 8 Comparison of tracer concentration decay curves obtained from water model and pulverized fuel furnace for varying degrees of swirl.[26]

At United Technologies Research Center (UTRC), East Hartford, Conn., a substantial effort also has been given to laser anemometer measurements of turbulent swirling combustion flows.[29] Measurements were made in the initial mixing region of a confined turbulent diffusion flame. The axial and swirl time-mean velocity profiles and the rms and probability density distribution of the velocity fluctuations show that there are significant variations of the mean and time-dependent flowfields with changes in ambient combustor pressure and inlet-air swirl. These variations have pronounced effects on pollutant emissions. Substantial large-scale contributions to the total rms turbulent velocity flowfield were found. These large-scale fluctuations result in large departures from Gaussian turbulence and significant deviations from isotropy over most of the initial region. Such large-scale motions indicate that turbulence models based on local equilibrium assumptions will not represent the physics of these combusting flows adequately. Representative time-mean axial and swirl velocity profiles at different axial stations, over the full range of ambient combustor pressure and swirl, are appended in the paper.

C. Pollutant Formation

Concentrating on pollutant formation in combustion, detailed experimental results for the influence of aerodynamic phenomena are available from UTRC.[30] Average concentration levels of the pollutants nitric oxide NO, nitrogen dioxide NO_2, carbon monoxide CO, and unburned hydrocarbons were measured at the exit of an axisymmetric combustor over a significant range of operating conditions. In addition, detailed species concentrations, temperature, and velocity maps were obtained throughout the combustor for several representative operating conditions. Gaseous fuel (natural gas, methane, or propane) issued through a central round tube, mixing and burning with the airstream within the 1.8-m-long cylindrical combustor. Liquid propane was used as the fuel in some of the tests. Major combustor input parameters were varied over substantial ranges: overall fuel-air equivalence ratio, 0.5-1.3; air-fuel velocity ratio, 0.1-40.0; inlet air swirl number, 0.0-0.6; air flow rate (kg/sec), 0.09-0.14; inlet air temperature (°K), 730-860; and combustor pressure (atm), 1.0-7.0.

It was found that elevated pressure and swirl result in a shift from chemistry- to mixing-limited behavior and create "unmixedness" in the flowfield, producing high local temperatures in an annular region around the centerline, which in turn enhances NO formation and consumption of hydrocarbons. Aerodynamic flame stabilization, achieved without the benefit of swirl or physical flame holders in systems having large air-fuel momentum flux ratios, produces strong stirring that results in reduced temperatures, low NO formation, and hydrocarbon consumption rates.

The NASA Lewis annular combustor includes a unique concept that has demonstrated substantial potential for lower oxides of nitrogen NO_x emissions.[31-37] The combustor is divided into 48, 72, or 120 individual swirl-can modules arranged in two or three concentric rows, respectively, which distribute combustion uniformly across the annulus. Early designs of these modules with swirler plates did not pay much attention to fuel atomization and mixing within the individual modules. It now is recognized that oxides of nitrogen, soot, and unburnt hydrocarbons formed in the small reaction zones can be frozen and omitted from the exhaust. More attention now is being devoted to the control of mixing and improvement of fuel atomization in each individual module, all of which now are designed specifically for low oxides of nitrogen emissions. Results show that swirl-can combustors produce oxides of nitrogen levels substantially lower than conventional combustor designs. These reductions are attributed to reduced dwell time resulting from short combustor length, and quick mixing of combustion gases with diluent air, and to uniform fuel distributions resulting from the swirl-can approach. At low power conditions, the levels of carbon monoxide and unburnt hydrocarbon emissions normally would rise to quite high values, but these can be reduced somewhat by radial staging of fuel into just one or two module rows. At present, a swirl flow annular combustor for test in-house is being designed, including radial fuel staging capability; it complements the swirl-can module approach and is discussed further in Sec. II. D.

Nitrogen oxides NO_x are formed (primarily as nitric oxide NO) during the combustion process as thermal NO (resulting from the high-temperature thermal fixation of atmospheric nitrogen in the air supply, as primarily with gas and oil fuels) or as fuel NO (resulting from the nitrogen in the fuel, as with oil and coal fuels). Thermal NO formation in gaseous systems has been studied extensively. The controlling mechanism in the postflame zone is an extended version of that proposed by Zeldovich. In the flame zone, significant amounts of NO are formed very rapidly as prompt NO, and these are believed to be the result of high oxygen atom concentrations produced by the hydrocarbon combustion process and of other undefined carbon-nitrogen reactions.[38] The mechanism for fuel NO formation is not well established, although recent work in-

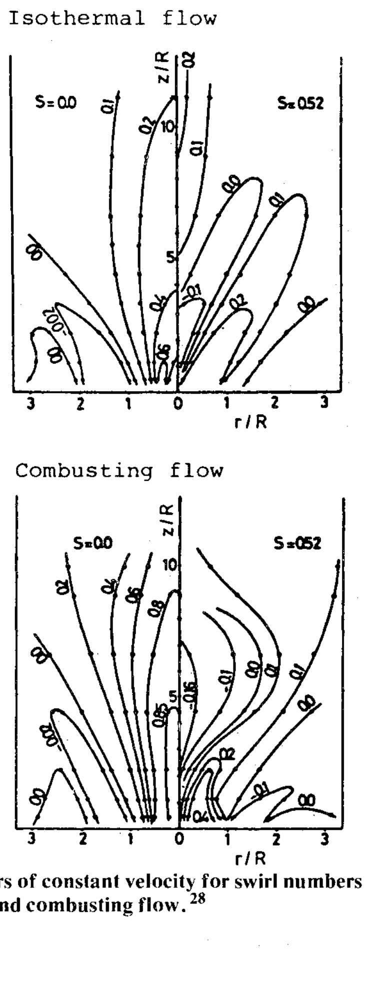


Fig. 9 Contours of constant velocity for swirl numbers of 0 and 0.52, for isothermal and combusting flow.[28]

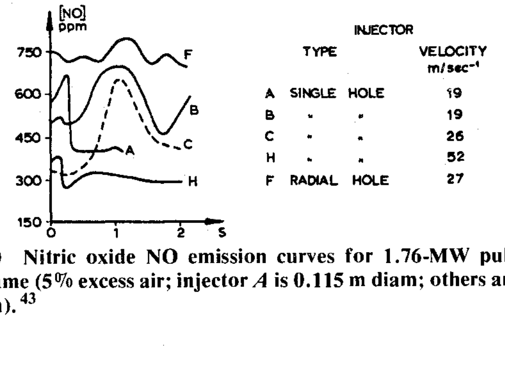


Fig. 10 Nitric oxide NO emission curves for 1.76-MW pulverized coal flame (5% excess air; injector *A* is 0.115 m diam; others are 0.060 m diam).[43]

dicates that it is the primary source of NO formation in pulverized coal flames.[148]

The evidence about the effect of swirl on pollutant formation shows that precise effects depend on the precise configuration being considered. As far as oxides of nitrogen NO_x are concerned, the effect of swirl may enhance its production or not. Generally, increased swirl 1) increases entrainment of cooled combustion products and thereby decreases thermal NO, 2) increases local oxygen availability and thereby increases fuel NO (and possibly also increases prompt NO), and 3) increases combustion intensity and so increases thermal NO.

Prompt NO may be dealt with under the second category, where swirl increases local oxygen availability. There are two effects of this. Hydrocarbon radicals react more with oxygen rather than forming a nitrogen-containing hydrocarbon radical, which is essential for the prompt NO mechanism,[38,39] and so reduce prompt NO formation. On the other hand, any nitrogen-containing free radical has more oxygen available with which to react, which leads to the greater production of prompt NO. There is no evidence as yet to decide which of these competing effects of swirl predominates. Details of other pollutant formation studies are relegated to the references[40-44]; other work is described in Sec. III. B., with additional referencing. As an example of the effect of swirl on the level of flue gas nitric oxide concentrations, for different types of fuel injector, Fig. 10 shows the results obtained at the International Flame Research Foundation, Ijmuiden, Holland, for pulverized coal flames.[43] Details of the fuel injectors used in these studies, and similar results for large-scale gaseous diffusion flames, are available in Ref. 44.

D. Centrifugal Effects

Recent work at United Technologies Corp., Florida,[45-48] and ONERA, France,[49,50] has been concerned with the favorable centrifugal force effects on combustion. Tests in a combustion centrifuge demonstrate that the increased "buoyancy" produced can increase flamespeeds significantly over turbulent flamespeeds, which control combustion rates in conventional burners. In the past, when attempts have been made to increase the turbulent flamespeed to higher values, the pressure drop required to produce the turbulence was prohibitive, or flame stabilization problems occurred at higher velocities. Tests show that centrifugal force can be used to increase flame propagation rates by an additional factor of 4 or more.[47]

The models were developed[47] to predict the flame-spreading rate at various burner conditions (bubble theory of flame propagation) and the extinction limits of flames at very high centrifugal force values (based on classical heat-transfer correlations), respectively. The effects of Reynolds number on turbulent flamespeeds and on limiting bubble sizes in gravitational fields also were measured. The validity of the experimental model was confirmed by testing a subscale 15-in.-diam swirl augmentor,[48] which uses precombustion swirl vanes to swirl the flow and produce a centrifugal field that increases the burning rate of the combustible mixture. Fuel is inserted into the swirling flow by spray rings, and the flame bubbles move quickly to the center because of the buoyant effect of the hot burned gases in the cold unburned gases, igniting the fuel-air mixture as they go. Since the bubble speed can be many times greater than turbulent flamespeed in conventional augmentors, shorter lengths or higher burning efficiencies result (see Fig. 11). The swirl augmentor has the added performance advantage of being unaffected by pressure and Mach number changes, and pressure losses are less than conventional augmentors. This has led to the design of a full-scale swirl augmentor, for advanced versions of an Air Force turbofan engine, which is predicted to reduce the fuel consumption and increase the stability of the engine.[47]

Guided by these studies, a swirl flow annular combustor is being developed at NASA Lewis Research Center. It has radial fuel staging capability. One outer row of swirl-can modules may be used exclusively under idle conditions. At other conditions, fuel also may be injected further inward, directly into an annular swirling flow region, caused by swirl vanes positioned around the annulus further upstream. At present, this swirl flow annular combustor is being investigated. A full-scale plastic model already has been built for flow studies, and tests currently are in progress with annular swirl vane angles of from 25° to 45°.

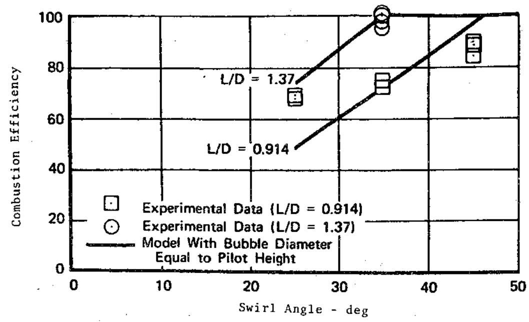


Fig. 11 Comparison of experimental and theoretical results at augmentor equivalence ratios between 0.95 and 1.05 (Ref. 48).

In general, the application of swirl in combustion systems, usually to the annular air surrounding the primary fuel outlet, leads to increased rates of mixing (higher turbulence) and a shorter, more intense stable flame. Under certain circumstances, however, swirl can have the opposite effect and lead to reduced rates of mixing (laminarization) and a longer lazy flame. Such an example is a turbulent jet flame, burning in the core of the rotating flowfield set up by the rotation of a cylindrical wire screen.[51,52] Without rotation, a typical turbulent jet flame is observed; with rotation, the flame becomes stably confined in the vortex core. This centrifugal stabilization of the flow reduces mixing and entrainment, leading to a considerable increase in flame length, up to a factor of about 5. Similar phenomena are observed in fire whirls, dust devils, tornadoes, hurricanes, waterspouts, etc., and characterizations of these geophysical phenomena are of great interest themselves.[53]

E. Vortex Effects

Swirling flows, with particular emphasis on the phenomenon of vortex breakdown (the formation of a free stagnation point and recirculation zone in the vortex core of flows with significant streamwise vorticity), have been studied for some time at Cornell.[54,55] A gas-turbine-like combustor using vortex breakdown to stabilize combustion has been investigated, where a confined double concentric jet configuration is used, with premixed fuel (methane) and air in the inner jet and air in the outer jet. Swirl may be induced in both inner and outer jets with the sense of rotation the same or opposite (coswirl or counterswirl). The objectives were to learn more about the influence of swirl and vortex breakdown on combustion and to evaluate the potential of this configuration as a practical device.

The double concentric swirler configurations of the various NASA Lewis swirl modules[31-36] (studied for application in aircraft jet engines) are very similar to those of the present study. Early studies of vortex breakdown indicate[54] that the size and position of the recirculation zone and its associated turbulence field could be influenced by swirl level, relative swirl direction, and jet velocity ratio. It seemed desirable and feasible to use these flow parameters to match flow conditions to operating conditions. Of special interest was the possibility of using a very lean inner jet to limit the formation of oxides of nitrogen NO_x (without sacrificing carbon monoxide CO and unburned hydrocarbon emission performance), coupled with a large recirculation zone and intense turbulence to counteract the loss of stability due to lean operation. Qualitative observations of the combustion process, blow-off limits, exhaust temperatures, and emissions of oxides of nitrogen NO_x and carbon monoxide CO from the combustor are reported in Ref. 54.

More recently,[55] composition, temperature, and velocity profiles have been presented for different values of swirl, equivalence ratio, and inner-to-outer jet axial velocity ratio. Combustion efficiency as determined by chemical and thermal analysis also was reported. Relative swirl direction and magnitude are found to have significant effects on exhaust gas concentrations, exit temperatures, and combustion efficiencies. Counterswirl generates a large recirculation zone, a short luminous combustion zone, and large slip velocities and turbulence in the interjet shear layer. Low nitric oxide NO levels are observed for maximum counterswirl conditions and lean mixtures. However, this is accompanied by low combustion efficiency, as indicated by the relatively high carbon monoxide CO and methane CH_4 levels and low exhaust gas temperatures. It is concluded that quenching due to rapid mixing in the interjet shear layer is the main contributor to this, and this is confirmed by results obtained by changing outer swirl and jet velocity ratio.[55]

It often has been assumed that the mean flow from vortex chambers is axisymmetric. Recent studies[56-58] have shown this to be true only for low swirl numbers and low Reynolds numbers. For a given swirl number ($S>0.6$), when the flow reaches a certain critical Reynolds number, the vortex breakdown instability develops. The initial manifestation usually is comprised of a nearly symmetric swelling of the vortex core, enclosing a recirculating bubble of fluid. In the wake of this disturbance, another spiral instability often occurs in which the central forced-vortex region starts to precess about the axis of symmetry. This so-called precessing vortex core lies near to the boundary of the mean reverse flow zone, which now has become quite large, between the zero axial velocity line and zero streamline, and it is responsible for the very high levels of turbulence and mixing which have been measured in swirl generators. There is now three-dimensional (3-D) time-dependent turbulent flow, which has dramatic effects on the stability, rate of mixing, combustion intensity, and flame length. The range of stable burning can be extended well into the region of fuel-lean mixture ratios. Although the precessing vortex core is useful for mixing the reactants, it can give rise to combustion oscillations and the emission of undue noise and other pollutants.[59] As the precessing vortex core leaves the exit, it soon is dissipated, and an axisymmetric motion ensues.

There is, however, another instability associated with the precessing vortex core and the exit. Near the throat region, the eddies and mixing processes are mainly in the tangential-axial plane, but at the exit a large eddy is formed in the radial-axial plane, just inside the path of the vortex core. This is stable at low Reynolds numbers, but as the Reynolds number is increased the eddy is shed alternately from either side of the exit. This is a continuous process, with the eddy being peeled off continuously by the precessing vortex core. It is called the radial-axial eddy. A schematic of the flow patterns occurring with the precessing vortex core is shown in Fig. 12.

It may be shown that the precessing vortex core can be characterized by intensity and frequency parameters.[56-58] Excitation of the frequency and amplitude of the precessing vortex core substantially increases the pressure loss, whereas damping reduces the pressure loss. A turbulent axial jet of fluid introduced along the central axis of the swirl generator reduces the rate and radius of the precession. With swirling combusting flow, either an intense excitation of the precession occurs, or a large-scale damping occurs, depending on the mode of fuel entry.

Premixed combustion appears to be the only method by which the precessing vortex core is excited to higher frequencies and intensities as compared to the isothermal state. A fairly linear relationship between frequency and Reynolds number is found for a combustion case, similar to that for an isothermal case. Frequencies are, however, increased by a factor of 2 or 4, dependent on flow rate and mixture ratios. Blow-off limits of this type of flame are wide. Any other mode of fuel entry (diffusion flame with axial or tangential entry) damps the precessing vortex core with large positive radial density gradients. Frequencies with axial fuel entry are some 50% higher than those for tangential fuel entry. Stability limits with tangential fuel entry are poor. Intensities for the oscillations substantially reduced for these two modes of fuel entry (as compared to very high values for the premixed flame), and the amplitude is damped by some 3 to 4 orders of magnitude. A nondimensional frequency parameter $f\ D^3/Q$ (where f is frequency, D is chamber diameter, and Q is mass flow) is shown to be adequate for describing the variation of frequency with Reynolds number, for both the isothermal and flame states.[56-58]

The unpleasant characteristics of the presence of a precessing vortex core in industrial burners can be improved by better control of both the aerodynamics and the distribution of reactants in the burner. With this objective, a multiannular swirl burner recently has been developed[59] which has wider stability limits, better turn-down ratio, and higher volumetric heat release rate than the conventional single annular tangential entry (or vane type) swirl flame stabilizer. High volumetric heat release rates are achieved matching the concentrations and directions of flow of reactants in such a way that regions of high fuel concentration overlap regions of high shear stress in the flow. No evidence of the precessing vortex core is found with this burner. The burner consists of eight concentric annular divergent nozzles, with the inner end of each nozzle aligned with the outer end of

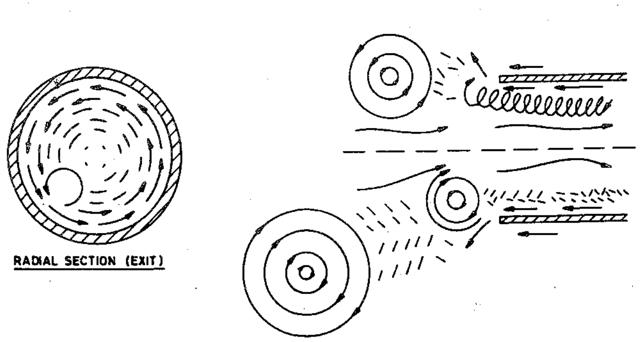


Fig. 12 Isothermal and premixed combustion flow patterns dominated by the precessing vortex core; note the large dissipative precessing vortex core inside the swirler and the radial-axial eddy being shed from the exit.[56-58]

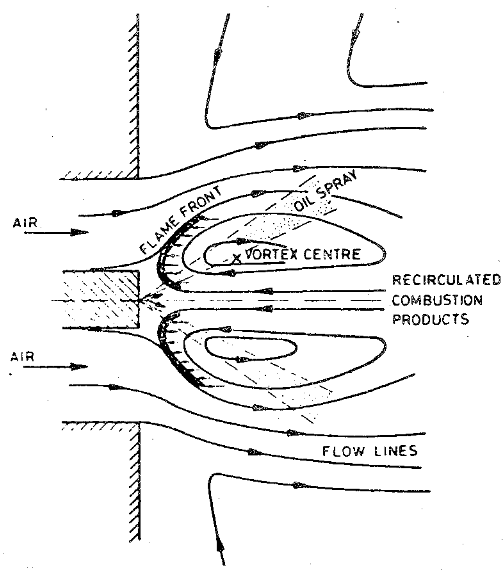


Fig. 13 Stabilization of pressure jet oil flame by internal recirculation zone in swirling annular jet.[4,60]

the adjacent inner nozzle. Fuel and air may be supplied tangentially to alternate annuli; tests are being made with alternate rings coswirling and counterswirling.

F. Liquid Fuel Flames

Other work has been concerned with liquid fuel flames.[61-70] Practical oil flames are usually in the form of one or two basic types.

1) The first type is turbulent jet diffusion flames, in which the oil is atomized by high-pressure air or stream (blast-atomized) and where the momentum of the fuel spray is so high that it is quite sufficient for the entrainment of combustion air necessary to complete the combustion. The significant dimensions of the flame, such as length and angle of spread, can be calculated from turbulent jet theory based on the fuel-atomizing agent spray as the momentum source.

2) The second type is pressure jet flames, in which the momentum of the spray is small in comparison with the momentum of the airflow. In this case, the characteristic dimensions of the flame will depend more on the airflow pattern than on the fuel spray.

The interaction of a pressure jet oil spray with the recirculation zone from a swirling annular jet in the Ijmiuden furnace is shown schematically in Fig. 13.[60] The figure shows streamline airflow patterns as calculated from mean velocity measurements under isothermal conditions, with details from oil flame photographs superimposed, so as to give the composite picture. In order to obtain flame stabilization, a region of the flowfield must be found where the flame speed matches the forward flow velocity, and also the heat supplied must be sufficient to initiate the combustion process. Within a recirculation zone, the forward flow velocity is reduced until it reaches zero at the reverse flow boundary, and thus a region of the flow always can be found where local flame speed will match local forward velocity. Since the recirculation eddy generally passes through the flame front, recirculation combustion products are carried toward the burner and pass through the spray, carrying small droplets to the flame front and thus forming a flame front, as shown in the figure. The size and strength of the recirculation zone can be controlled by the degree of swirl in the airflow system. By adjusting the angle of the oil spray to match the size and strength of the recirculation zone, optimum conditions can be found for good flame stabilization, high combustion efficiency, and minimum production of pollutants.[61] Recent work on liquid fuel swirling flames is discussed in Refs. 63-70.

G. Summary

To summarize the experimental evidence, the design of swirl burners for practical combustion equipment is still very much an art in which the practical experience of the designer is paramount.[61] The use of bladed swirlers is one of the most effective means of generating swirl, and there does not appear to be a very significant difference between flat-bladed and aerodynamically shaped swirler blades. An outlet diffuser increases the size of a recirculation zone, and the use of a divergent angle of 35° and a diffuser length of 1.5D has provided good results in practice. The ability to move the swirler in the burner along the outlet diffuser is a simple and effective means of controlling the degree of swirl. Some simple aerodynamic measurements of the flow distribution at inlets to the windbox and the shape of the reverse flow zone using a total head tube with forward- and rear-facing holes can be of considerable help to the burner designer. In oil-fired flames, the matching of the spray angle to the flow patterns within and around the recirculation zone is important in order to minimize smoke formation in the outer or inner regions of the flame. The objective of current research is to characterize these types of flows in a logical scientific fashion, so aiding future designers.

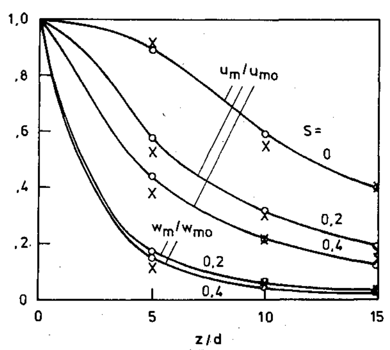


Fig. 14 Prediction of longitudinal decays with swirl for inert jets (× experimental, 0 predicted).[123]

III. Modeling and Prediction

A. Basic Governing Equations

In the modeling and prediction of swirl flow combustion, one is involved with simulating the problem via simultaneous nonlinear partial differential equations. These may be parabolic (boundary-layer type) but are more often elliptic (recirculating type), and the solution scheme differs according to the category and is discussed in Sec. III. C. The turbulent flux (Reynolds) equations of conservation of mass, momentum, stagnation enthalpy, and chemical species, which govern the flow of turbulent chemically reacting multicomponent mixtures, may be solved for time-mean pressure, velocity, temperature, and species mass fractions, provided that 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 lead to many simplifications. The reaction then is 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-breakup concepts.

Further equations are required to simulate turbulence, two-phase effects, radiation, pollutant formation, etc., but a central point of the theory is that all of these equations are similar to laminar flow ones, but the variables are time-mean quantities, and the fluxes for momentum, stagnation enthalpy, and the chemical species are composed of two parts, the laminar and turbulent parts, the latter of which are related to correlations of turbulent fluctuations. These 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_{rz}. In turbulence theory, isotropy is the term that connotes the existence of a scalar turbulent viscosity at points in the flowfield. If the turbulent viscosity is not equal with regard to different stress-rate of strain directions, the term nonisotropy is used, and the ratios of the other component with the primary component of turbulent viscosity are called $r\theta$ (and other) viscosity numbers, by analogy with Prandtl-Schmidt numbers.

All of these linkages and complexities in the equations provide a high degree of nonlinearity in the total problem and give the numerical analysis of fluid flow its peculiar difficulty and flavor. The similarity between the differential equations and their diffusional relations allows them all to be put in the common form

$$\frac{\partial}{\partial t}(\rho\phi)+\mathrm{div}(\rho v\phi-\Gamma_\phi \mathrm{grad}\phi)=S_\phi \tag{3}$$

where the exchange coefficient assumptions have been invoked. Here ϕ is a general dependent variable, and equations may be solved for ϕ equal to time-mean axial, radial, and swirl velocities u, v, w, stagnation enthalpy h, fuel mass fraction m_{fu}, mixture fraction f, turbulent kinetic energy k, and dissipation rate ϵ, and mean square fluctuating component of fuel concentration $g=\overline{m_{fu}'^2}$ (and possibly other variables as well). The equations differ not only in their exchange coefficients but also, and primarily, in their final source terms S_ϕ. Specific details about the equations may be found in the literature.[1,71-80]

B. Simulation of the Physical Processes

Closure and completeness of the governing equation set are effected by means of models of the physical processes taking place within the combustion system. Either our knowledge of these processes or computer size limitations restrict the degree of sophistication to be used in any simulation. The simulation problems have been reviewed extensively elsewhere[71-80] and will be touched on only obliquely here. Briefly, the four main processes to be modeled are as follows:

1) Turbulence, where models of the exchange coefficient type and direct stress specification type have been applied to swirling flows, and currently energy-length models are to be recommended and in particular the $k=\epsilon$ model, where $\epsilon = k^{1.5}/\ell$, and ℓ is the macrolength scale of turbulence.[81,82] A recent conference highlights current work in this area.[83]

2) Radiative transfer, where the integrodifferential equations may be represented by Hottel's "zone method"[84] or one of the "flux methods" for one, two, or three flux sums.[78,85] (The former is more exact but difficult to incorporate with hydrodynamics; the latter is less rigorous but simple to employ.)

3) Chemical reaction, including the simulation of premixed and diffusion flames,[71,86] the complex equations representing the route to pollutant formation,[87-95] techniques for handling "stiff" kinetics[96-104] (where widely differing reaction rate coefficients require special techniques for handling source terms), and the effect of turbulence structure on time-mean chemical reaction rates.[86,105-111] Realistic simulation of complex chemistry in turbulent reacting flows is probably *the* area in combustor modeling which will prove to be most useful to study, and the results of which will be most fruitful to apply in practical design situations.[112]

4) Two-phase phenomena, for solid fuel particles and liquid droplets, including infinite drag assumptions for small particles[113] and ordinary differential equations for larger particle trajectories,[114] and studies on the rate of burning of droplets, clouds, and sprays.[115-118]

C. Computational Methods

All combustor problems entail the solution of many simultaneous nonlinear equations, including up to three velocity components, pressure, stagnation enthalpy, and species concentrations. Since their equations are all similar in form, the same solution algorithm can be used for all of them. Problems are classed according to the degree of realism and refinement, as represented by their dimensionality (the number of independent variables from three space dimensions and time) and type (parabolic or elliptic). The flow classification of parabolic [possessing one coordinate direction with first- but without second-order derivatives: boundary-layer type with prominent directions(s)] or elliptic (possessing second-order derivatives in all coordinate directions: recirculating type with upstream influence) governs the type of boundary conditions required and solution method. Marching methods are appropriate for the former (flows with weak swirl) and relaxation methods for the latter (flows with strong swirl). The problems, methods, and solutions are discussed in Refs. 119-147. Papers presented at two recent conferences highlight both experimental and theoretical studies in the fluid mechanics of combustion.[146,147]

Problem classification is generally into one of the following categories:

1) 2-D marching methods, for axisymmetric 2-D parabolic boundary-layer flows: weak swirl (approximately $S<0.4$), 1-D storage, automatic expanding grid using non-dimensionalized streamfunction ψ instead of r as the radial coordinate, and implicit solution procedure.[122-125]

2) 2-D relaxation methods, for axisymmetric 2-D elliptic recirculating flows: strong swirl (approximately $S>0.6$), 2-D storage, streamfunction-vorticity $\psi=\omega$ or primitive pressure-velocity p-u-v formulation, and Gauss-Seidel or line-by-line SIMPLE (semi-implicit method for pressure-linked equations) solution procedure.[126-138]

3) 3-D marching methods, for 3-D parabolic boundary-layer flows: nonaxisymmetric, weak swirl, 2-D storage, primitive formulation, and SIMPLE solution procedure.[128-145]

4) 3-D relaxation methods, for 3-D elliptic recirculating flows: nonaxisymmetric, strong swirl, 3-D storage, primitive formulation, and SIMPLE solution procedure.[138-145]

The essential differences between the various available computer codes (and those that are not available) include the complexity of the equation set for the simulation of the physical processes, the storage requirements, the location of variables in the grid space system, the method of deriving the finite-difference equations that are incorporated, and the solution technique. In primitive pressure-velocity variable formulations, a staggered grid system normally is used, as recommended by Los Alamos for its special attributes. In computational fluid dynamics, the "best" representation of the convection and diffusion terms is essential to the accuracy and convergence or stability of the iteration scheme or marching procedure. At high call Reynolds numbers, a certain degree of "upstream differencing" is essential using upwind differencing, a hybrid formulation or the Los Alamos zip, donor cell, etc., techniques, for example.[75] Solution procedures vary from Gauss-Seidel point methods[67] to more efficient line-by-line SIMPLE methods[68,74] for steady-state problems, with corresponding explicit and SIMPLE methods for associated transient problems. The application of finite-element computational methods to combustor problems, with complex boundary geometry and complex boundary conditions to apply, is in its infancy; further work in this fertile area will be most useful.[137]

IV. Sample Predictions

Calculations often are performed with a nonuniform grid system of about 500 nodes in the flowfield, and the solution time required to solve 10 simultaneous equations is typically 10 min of CDC 6600 CP time, although this decreases in the absence of swirl to about 5 min and in the absence of swirl and combustion to about 2½ min. Most relaxation procedures for elliptic problems are under-relaxation on new values, coefficients, and source terms, although this under-relaxation is set to be less effective as the iteration procedure nears convergence, so that the initial stabilizing effect does not hinder the final convergence rate. Final convergence is decided by way of the well-known fractional-change criterion or the residual source sum criterion, the latter generally being recommended. The results discussed below compare experimental evidence and predicted characteristics of weakly and strongly swirling, free and confined, jets and flames.

A. Weakly Swirling Flows

Since details of the prediction of weakly swirling jet and flame structures have been published already, only highlights of the computations are discussed here. Predictions are made with both the Prandtl mixing length and energy-length turbulence models so as to confirm suitable extensions of the models to swirl flows.[123] Computations with either model produce longitudinal decays of u_m and w_m which compare well with experimental data (see Fig. 14). The primary use of swirl in a jet is to increase the angle of spread and rate of decay of axial velocity. The half-angle α $(u/u_m = 0.5)$ is predicted to increase with swirl according to

$$\alpha = 4.8 + 14\,S \quad (4)$$

as found experimentally.[4] These and other results[123] agree well with the data and show that the effect of swirl on isothermal jet growth, entrainment, and decay may be predicted well. To make such isothermal computations, one has to solve four simultaneous parabolic partial differential equations for u, rw, k, and Z, where $Z = k^m \ell^n$. The computation cited uses $m = n = 1$.

Premixed flames $(m_{fu} = 0.245)$ with initial fuel/air ratio well outside the flammability limits have been studied experimentally.[4] Predictions have been made[125] with an eddy-breakup reaction model and turbulence simulated in a manner similar to the form used in the prediction of inert jets.[123] Eight parabolic partial differential equations are solved for u, rw, k, $k\ell$, h, m_{fu}, $m_{ox} - i m_{fu}$, and g. Predicted longitudinal decays of u_m and w_m compare well with experimental results, and there is a progressive increase in them as S increases. It is to be noted, however, that the velocity decays are slower than in cold swirling jets. This is largely because of the temperature and density changes, and a consequence of this gas expansion is increased axial and radial velocities, giving a reduced rate of decay of u_m and a wider jet initially.

Figure 15 shows longitudinal variations with swirl of T_c, the centerline temperature, and $\dot{m}_{fu}$, the total mass flow rate of unburned fuel.[125] Notice that T_c increases more rapidly as S increases, indicating the more rapid mixing of hot combustion products with the cooler, higher-velocity core region. Observe also that $\dot{m}_{fu}$ decreases more rapidly as S increases, indicating the more rapid consumption of fuel per unit length of flame. Predicted flame front lines (loci of temperature maxima) accord well with the experimental ones of Fig. 4, and it is clear that the length of the flame decreases markedly with swirl and that there is a progressive increase in the initial width (at $z/d = 10$) of the flame as S increases. Flame lengths may be compared favorably with experimental values, as Table 1 shows. Downstream development of these jets and flames often is characterized by the parameters A (for axial velocity decay) and α (for jet half-angle), defined by

$$u_m / u_{mo} = A\,(\rho_\infty / \rho_{min})^{0.5}\, d / (z + a) \quad (5)$$

$$\tan\alpha = r_{0.5} / (z + a) \quad (6)$$

where m stands for station maximum, o for orifice value, ρ for density, ∞ for ambient conditions, and min for minimum value. Recommendations for a, A, α, and flame lengths are given in Table 1.

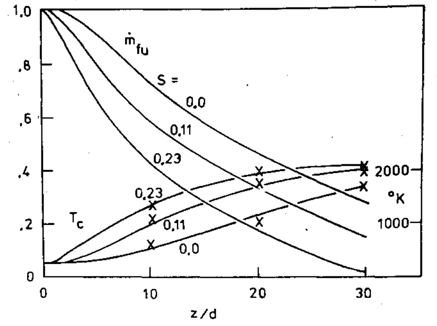


Fig. 15 Predicted longitudinal T_c (centerline temperature) and $\dot{m}_{fu}$ (mass flow rate of unburned fuel) variations for partially premixed jet flames ($m_{fu} = 0.245$) (× experimental).[125]

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$/d$	...	$43 - 100S$

B. Strongly Swirling Jets

The forms of strongly swirling free and enclosed jets, issuing from vane swirlers and swirl generators, have been predicted using the p-ω and p-u-v approaches.[74,128] The problem is elliptic, requiring the relaxation solution technique. Initially, enclosed flow in a cylindrical chamber was predicted solving three equations for ψ, ω/r, and rw with a simple algebraic turbulent viscosity formula.[74] Results for the length of central recirculation zone, axial distance to impingement, and velocity decays are encouraging when compared with experimental data, in view of the use of a naive turbulence model in the computations. More recently, the primitive-variable approach has been used to predict similar flows; then equations are solved for p, u, v, w, k, and ϵ (where the additional complexity of the two-equation k-ϵ turbulence model has been included). Again results show good agreement with experiment.[128] As an example, Fig. 16 shows predicted streamlines and recirculation zone for a free annular jet from an axial-plus-tangential entry swirl generator with swirl number $S = 1.5$. There is a striking resemblance to a similar experimental figure (see Fig. 1), but the recirculation zone is predicted slightly too wide and too short.

An enclosed swirling flow in an axisymmetric furnace configuration recently has been predicted[76] by an advanced primitive code with advanced turbulence and combustion models. The predictions with chemical reaction suppressed are discussed here (those with chemical reaction are discussed in the next section); for brevity, only those for axial velocity distribution are considered. Figures 17 and 18 show predicted

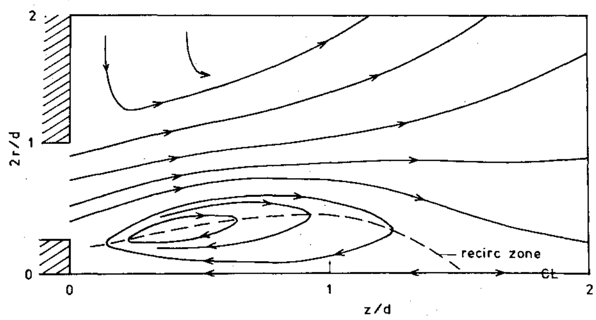


Fig. 16 Predicted streamlines (—) and recirculation zone (---) for a free annular jet (from an axial-plus-tangential entry swirl generator) with swirl number $S = 1.5$ (Ref. 128).

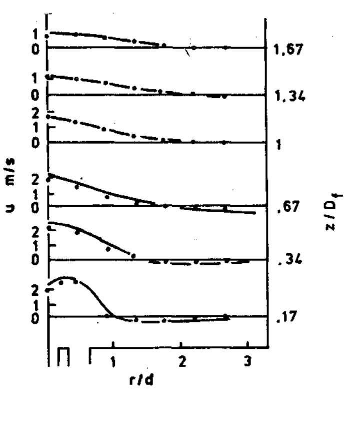


Fig. 17 Radial profiles of mean axial velocity: swirl number = 0, isothermal flow.[76]

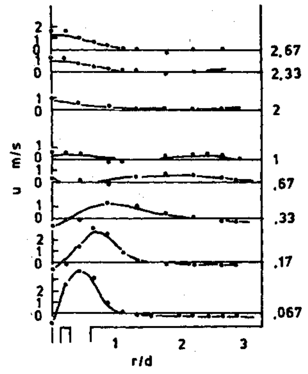


Fig. 18 Radial profiles of mean axial velocity: swirl number = 0.52, isothermal flow.[76]

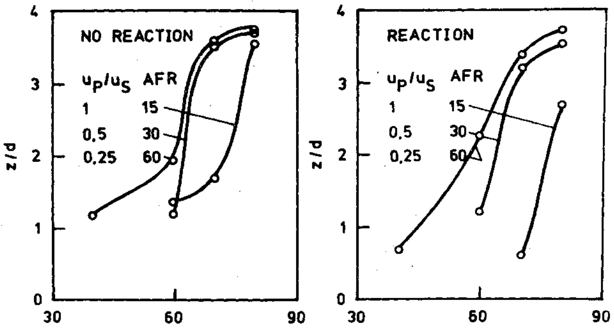


Fig. 20 Effect of swirl vane angle on central recirculation zone length (0 predicted).[74]

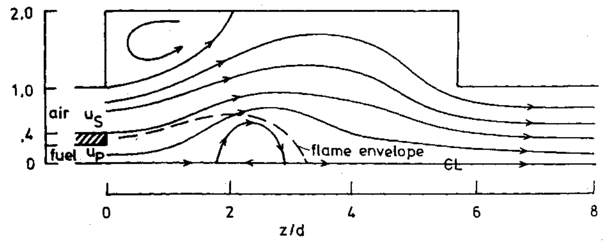


Fig. 19 Predicted streamlines (—) and flame envelope (---) in a combustion chamber (swirl vane angle 60°, primary velocity $u_p = 0.5\, u_S$, overall air-fuel ratio 30:1).[74]

axial velocity radial profiles at a variety of axial stations (D_f is furnace diameter) and compare them with experimental data for $S = 0.0$ and 0.52, respectively. In each case, there is no central jet velocity. Predicted results are very close to the measurements. Some of the effects of swirl are apparent immediately: a recirculation zone near the nozzle, off-centerline maxima, and more rapid decay in the downstream direction. Although not shown here, absolute values of turbulent kinetic energy are much higher (a factor of 3) in the swirling case in the initial region and extend further in the radial direction. However, their decay in the downstream direction is also quicker, indicating again that the interesting part of the flowfield is shorter and wider with the application of swirl.

C. Strongly Swirling Flames

Predictions for a strongly swirling diffusion flame in a cylindrical combustion chamber require the use of a 2-D elliptic program. In Refs. 74 and 126, a streamfunction-vorticity formulation is used, solving four partial differential equations for ψ, ω/r, rw, and f. A simple algebraic formula is used to specify the turbulent viscosity. Figure 19 illustrates a computation[74] for a cylindrical combustion chamber which has many of the features of practical equipment: fuel and air input at one end, exit for combustion products at the other, arrangement of the air inlet as an annular orifice surrounding the fuel inlet, a device for causing the air to enter with a swirling motion, and a thick annular lip between the air and fuel inlets. The expansion ratio D/d is 2. Sizes are such that equal axial velocities of the primary fuel stream u_p and secondary airstream u_S give overall stoichiometric conditions (air-fuel ratio AFR = 15). 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: pressure $p = 25$ atm, temperature $T = 850$ K, and $u = 36$ m/sec.

The computations show some interesting features[74] and striking differences between the nonswirling and strongly swirling (vane angle $\phi = 60°$ corresponding to a swirl number $S = 1.2$ approximately) cases. The presence of strong swirl causes a toroidal vortex to form in the middle of the combustion chamber, in addition to the recirculation near the entrance provoked by the sudden enlargement of the cross-sectional area. It also shortens the flame. Both of 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. 20 is the length of this zone as a function of vane angle ϕ for a variety of values of u_p (and hence AFR): on the left when no reaction is allowed to take place, and on the right with reaction.[74] In both cases, 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. The third point to note is that, with chemical reaction suppressed, zone lengths generally are longer: the presence of reaction, gas expansion, and increased velocity tend to shorten, and in some cases destroy (for example, 60° vanes with $u_p = u_S$), the zone as compared with its nonreacting counterpart. Despite this, zone lengths for low values of u_p (high values of AFR) are quite comparable, especially at higher degrees of swirl. This is because in these cases the flames are short and trapped upstream of the recirculation zone as opposed to encompassing it. Predicted also, and as expected experimentally, is that reduction of u_p (increase in AFR) and/or increase in vane angle ϕ progressively reduces the flame length and improves the temperature traverse quality (uniformity of temperature) across the exit from the combustor. Some general observations are that the presence and increase in size of a central recirculation zone are 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 of swirl vane angle, and suppressing chemical reaction.[38] For combustors, an optimum swirl strength for reasonable recirculation zone and pressure loss is about $S = 1.15$ or swirl vane angle $\phi = 60$ when $D/d = 2$, although recent work suggests that S based on chamber diameter D rather than nozzle diameter d gives a better guide to similarity of flow downstream of the inlet for different D/d systems.[22]

More recently, a strongly swirling enclosed premixed flame has been considered with a primitive pressure-velocity variable code, suitably amended to include the k-ϵ turbulence model and the simple exothermic one-step chemical reaction.[128] The results of application of the aforementioned advanced primitive-variable code (with advanced turbulence and combustion models) to flows with chemical reaction now are discussed.[76] Three combustion models are considered: model 1, diffusion flame; model 2, diffusion flame with thick flame region because of turbulence, calculation of g required from its governing partial differential equation; and model 3, finite reaction rate, deduced from the lesser of the Arrhenius and eddy-breakup models, calculating g either from its governing partial differential equation or its reduced local-equilibrium algebraic equation. Figures 21 and 22 show sample calculations of axial velocity at $x/D_f = 1.0$ and 1.5, at swirl numbers of $S=0.0$ and 0.52, respectively. Results show the presence of a central toroidal recirculation zone, and further downstream more uniform velocity profiles across the chamber, in the swirl case of the latter figure. Comparison with experimental data suggests that combustion model 2 is slightly preferable over model 3, with model 1 a poor third. This results from inadequacies in the detail of model 3 rather than the concept of recognizing finite-rate chemical reactions. Temperature field calculations are in close agreement with each other, but unfortunately there are no experimental data with which to compare them. These and other results show clearly the effect of swirl on furnace flames, both experimentally observed and theoretically predicted: swirl generally leads to flatter, more uniform velocity distributions across the chamber, a wider region of higher temperature shifted further away from the axis, and higher initial values, but lower later values, of kinetic energy of turbulence.

D. Three-Dimensional Flows

The discussion is restricted to two particular combustor flows: one[78] is a furnace flame without swirl, and most of the interesting part of the flow is without axial recirculation; and the other[79,139] is the flame in a section of an annular combustor, where the inlet boundary conditions favor the generation of a swirling motion in the flowfield. Figure 23 shows the results of computations for a steady methane diffusion flame in a square-sectioned adiabatic furnace, where dimensions and conditions are similar to those used experimentally in the Ijmuiden furnace.[78] In this preliminary work, no advanced turbulence model was incorporated, the turbulent viscosity being computed from a simple algebraic expression that gives approximate turbulent jet values of turbulent viscosity in the inlet jet part of the flow. The results show cross sections of the flowfield at four locations *A, B, C,* and *D*, going downstream in the flow direction from left to right. Contour plots in the frames allow interpretation of the entire 3-D flowfield of regions of unburnt fuel and temperature. Results that are not shown here indicate that the forward-moving jet of fuel quickly entrains the combustion air, causing a recirculation of hot combustion products in the corner regions, from which the further entrainment by the jet is supplied. Of course, the symmetrical entry of the fuel and air, and the absence of swirl, insures no circulation of gas in the sectional plane: all vector velocities in the cross sections are radially outward from the main-direction centerline. Inspection of the results shown in the figure reveal other physically realistic features: the flame boundary, taken to be the fuel-air interface, widens at first with distance from the injector nozzle, and then diminishes to zero; temperature maxima occur at the flame envelope; and nonuniformities of temperature diminish as the furnace exit is approached.

The second flow considered is a diffusion flame in a section of an annular combustor, shown schematically in Fig. 24.[79,139] Twelve equations are solved, including those for the two-equation k-ϵ turbulence model and a six-flux radiation model. The flow is fully 3-D and exhibits a complex recirculation pattern. A significant swirling motion develops mainly because of the upstream injection of dilution air along the top boundary, but also because of the spreading of the fuel jet flame and the circulation produced by the lateral air. The location and angle of injection of the lateral air also contribute to significant axial recirculation against the main flow direction. The discussion here is restricted, however, to the ensuing temperature field and, in particular, to the temperature distribution at the outlet, which is especially interesting to the combustion-chamber designer who wishes to have a good temperature traverse quality.

Several outlet temperature distributions are shown in Fig. 24, each resulting from a different set of inlet boundary conditions. Part A represents the standard situation: fuel and air entering at 600 K at all locations, fuel and top wall film cooling air entering at 100 m/sec, some inlet air through holes at upstream boundary averaged as 1 m/sec over the entire

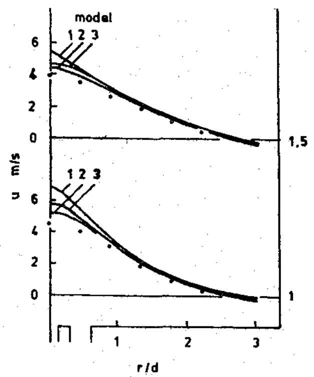


Fig. 21 Radial profiles of mean axial velocity: swirl number = 0, combusting flow.[76]

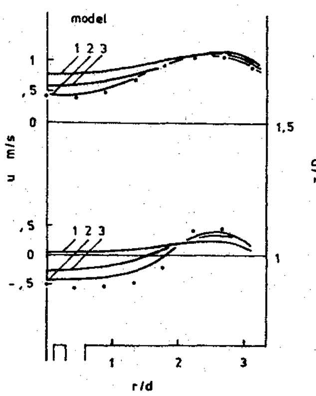


Fig. 22 Radial profiles of mean axial velocity: swirl number = 0.52, combusting flow.[76]

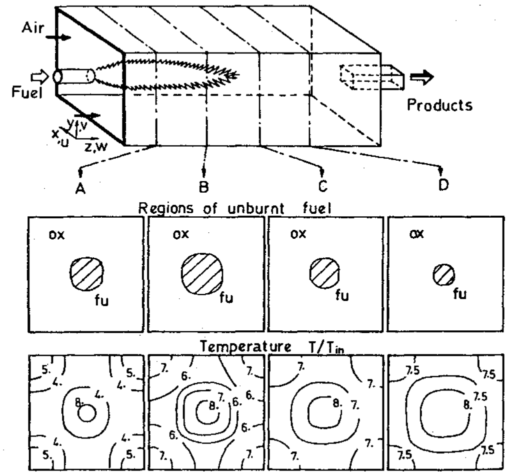


Fig. 23 Predictions for a diffusion flame in an adiabatic furnace.[78]

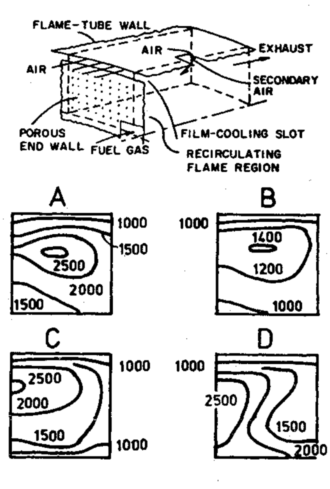


Fig. 24 Influence of boundary conditions on outlet temperature distributions for an annular combustor.[79,139]

area, and lateral air entry 200 m/sec normal to the top surface and -200 m/sec in the axial z direction, that is, at 45° in the upstream direction. Part B shows what happens when the top wall air film is injected at five times its standard value: the uniformity of the temperature is significantly greater. Comparison of the part C and part D contours with those of the standard result of part A reveals that the direction of entry of the lateral air radically alters the temperature pattern and does so in an understandable way. For the standard condition of part A, the axial velocity of the 200-m/sec vertical velocity lateral air is -200 m/sec, in part C it is 0 m/sec and in part D it is $+200$ m/sec. Clearly these and other design variations in boundary conditions are simple to incorporate and can be of great help to the combustor designer. The temperature distributions here are far from uniform; none of the ones shown is good enough from the points of view of efficiency and turbine inlet temperature requirements. Clearly the combustor being considered is not at a stage of development which the engine designer could accept.

V. Closure

The extremely favorable effects of applying swirl to injected air and fuel in combustion systems have been known and utilized for many years. Only recently, however, has systematic study been aimed at understanding and characterizing the observed phenomena. Advances in the experimental study, modeling, and prediction of combustor swirl flows were reviewed here. Increasingly detailed experimental observations are being modeled with increasing realism, both in the simulation of the physical processes occurring and solution of the resulting governing equations. A few general hypotheses now are linking together a large number of previously disconnected experimental data and being incorporated into general computer programs. Practical application of numerical predictions now is providing designers with adequate results more cheaply and quickly than currently possible by experimental means, which, in turn, is providing a powerful stimulus to their further development.

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