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Aspects of the Design of Swirlers as used in Fuel Injectors for Gas Turbine Combustors

C. A. MARTIN
Gas Turbine Fuel System Division
Parker Hannifin Corp.
Cleveland, Ohio 44112

An attempt is made to review the state of the art, in swirler design and performance, as it applies to airblast atomizers. The purpose of this review is to summarize existing information on swirler design aspects and performance, as well as to clarify and initiate the standardization of terminology relating to swirlers and swirling flow.

First, a brief, general discussion is presented on characteristics of swirling flows. Next, the more common methods of swirl production are described, followed by a more specific investigation of swirl vane design and performance. Finally, existing swirler terminology is presented and critically assessed, including suggestions for standardizing certain key terms.

NOMENCLATURE

E	Efficiency of Swirl Generation
E_L	Efficiency of Swirl Generation (According to Leuckel)
E_m	Efficiency of Swirl Generation (According to Mathur)
u	Mean Value of Axial Velocity Component
δ	Swirl Coefficient
P_o	Stagnation Pressure Total Pressure
ΔP	Static Pressure Drop
S_S	Swirl Strength
q	Volumetric Flow
D	Large Diameter of Annulus; Depth of Turning Channel
$B.R.$	Blockage Ratio
ψ	Blockage Factor
θ	Sweep Angle of Blade Leading Edge, Angle of Rotation
σ	Solidity
α	Blade Angle
C	Resistance Coefficient
C_R	Relative Resistance Coefficient (Static Pressure drop/weight flow)^2
ΔH	Loss of Total Pressure
V	Total Velocity Value
W	Width of Turning Channel
α_o	Reference Blade Angle
α_c	Canting Angle of the Blade
C	Blade Chord
S	Distance Between Blades, Gap
S	Swirl Number, Swirl Strength [See Eq'n (3)],
G_θ	Axial Flux of Annular Momentum [5] (Eqn 3)

$$G_\theta = 2\pi \int_o^\infty (\rho v_x v_\theta - \tau_{\theta x}) r^2 dr$$

G_x	Axial Flux of Axial Momentum

$$G_x = 2\pi \int_o^\infty (\rho v_x - \tau_{xx} + (p - p_\infty)) r\, dr$$

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ρ Mass Density

V_x Axial Velocity Component

V_θ Tangential Velocity Component

$\tau_{\theta x}$ Turbulence Shear Stress Component

τ_{xx} Turbulence Shear Stress Component

P Local Static Pressure

P_∞ Ambient Static Pressure

R Radius(Reference) Radius of Turning Corner

R_o Outer Radius of Annulus

S' Modified Swirl Number [See Eq'ns (4) & (5)]

G'_θ Modified Axial Flux of Angular Momentum

$$G'_\theta = 2\pi \int_0^R \rho u w r^2 dr \qquad \text{Eqn 4}$$

Modified Axial Flux of Axial Momentum

$$G'_x = 2\pi \int_0^R \rho u^2 r dr \qquad \text{Eqn 4}$$

$$G'_x = 2\pi \int_0^R \rho \left[u^2 + (w^2 - w_{MAX})/2\right] r dr \qquad \text{Eqn 5}$$

d Diameter(Reference),Inner Diameter of Annulus

u Axial Velocity Component

v Radial Velocity Component

w Tangential Velocity Component

r Local Radius

Introduction

In the design of gas turbine combustors steps must be taken to ensure that combustion can be sustained over a wide range of operating conditions. It is now well established that the most important factor governing flame stability is the primary-zone airflow pattern ref. [9]. Many different types of airflow patterns are employed, but one feature common to all is the creation of a toroidal flow reversal that entrains and recirculates a portion of the hot combustion products to mix with the incoming air and fuel. These vortices are continually refreshed by air admitted through holes pierced in the liner walls, and is supplemented by air flowing through an air swirler located in the combustor dome. Since the advent of airblast atomizers, a large proportion of this swirler air flows through swirlers located within the atomizer itself. When this swirling air emerges from the atomizer, carrying the fuel drops along with it, it exerts a strong influence on the stability and intensity of combustion, as well as on the size and shape of the flame region. Thus, in the design of airblast atomizers for advanced turbojet engines, these aerodynamic considerations demand as much attention as the attainment of high atomization quality. In this paper an attempt is made to review the state of the art in swirler design and performance as it applies to airblast atomizers. The purpose of this review is to summarize existing information on swirler design aspects and performance, as well as to clarify and initiate the standardization of terminology relating to swirlers and swirling flow.

First, a discussion is presented on characteristics of swirling flows in general. Next, the more common methods of swirl production are described, followed by a more specific investigation of swirl vane design and performance. Finally, existing swirler terminology is presented and critically assessed, including suggestions for standardizing certain key terms.

Swirl

Swirl is a very important element, necessary for the proper operation of a modern gas turbine fuel nozzle. Swirl is used to control the spray angle in order to ensure proper fuel placement as well as to prepare the fuel for proper filming and atomization. In most gas turbine fuel nozzles, both the air and the fuel are normally swirled.

The introduction of swirl to a fluid jet can produce a variety of results depending on both the swirl number as well as the Reynolds number. As the degree of swirl is increased in a turbulent jet there is a marked increase in jet width which accompanies the associated increase in the rate of fluid entrainment. The increase in jet axial decay rate which results, can set up adverse axial pressure gradients which in turn can produce flow reversals and recirculation.

Highly swirling flows exhibit a complex behavior with several different instabilities and flow patterns possible. As the swirl number and Reynolds number are increased, an instability called "vortex breakdown" occurs, followed by forms called "axisymmetric", "spiral" and "double helix", breakdown. These instabilities are not necessarily all symmetric in flow pattern, as the flow may cling to one side of the enclosure or even precess. These instabilities can obviously cause problems in swirl stabilized combustors, if not controlled.

Swirl Generation Methods

The methods of swirl generation in a fluid stream may be divided into five principal categories:

1. Tangential entry [1] [18] [19]

2. Axial guide vanes [1] [6] [10] [13]

3. Vortex generators [12]

4. Rotational mechanical devices. This includes rotating vanes, grids or rotating tubes [1]

5. Hybrids of the others

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Examples of 1,2, & 3 are illustrated in Figure 1, and described in the given references.

Axial swirlers or guide "vanes" are the most common method of swirl generation in gas turbines and airblast atomizers, as well as other practical systems. Vane swirler designs can vary significantly from one manufacturer to another, but most fall under the classification of either straight or curved vanes. As with many applications, the design of a swirler in atomization nozzles is usually selected first for reasons of ease and economy of manufacture and second for "efficiency" of operation. The next section will discuss specific design parameters and performance characteristics of practical swirl vane designs.

Swirler Design

When this study was initiated the first areas of literature that were investigated were spray nozzles and atomization. When this showed only limited swirl design literature [1], [5], [13], ducts with turning vanes and wind tunnel design [2],[3],[4], [11],[14],[15],[16],[17] were investigated.

The available evidence indicates, as would be expected, that gradual corners are more efficient and have lower pressure losses than abrupt, sharp-angled bends. [4] However, their use is not always practical due to space and cost limitations. Often, the losses due to more abrupt corners may be overcome by optimizing other design parameters. One common term used to characterize losses is the resistance coefficient, defined by [15]:

$$C = \frac{\Delta H}{\rho \frac{V^2}{2}} \qquad (1)$$

For the corner shown in Figures 2a, it has been found that the resistance coefficient is lowest when the values of both R/D and W/D are large. See Figures 2b and 2c. It also appears that the uniformity of the stream leaving the corner is greatest when these ratios are large. While it is usually possible to arrange for a moderately large R/D, it is often impractical to have a large W/D. The difficulty can be overcome by splitting the corner into a number of narrow cells by the introduction of a cascade of turning vanes parallel to W. See Figure 3. Such vanes usually lead to appreciable increase of aerodynamic and energy efficiency. One limitation imposed however is the additional skin friction experienced.

Many existing wind tunnels employ vanes of airfoil sections similar to those shown in Figure 4 [11] (c), (d), (e), (f). With all types of vanes it is found that the resistance coefficient of the corner depends on the ratio of the gap between the vanes to the vane chord (The chord is measured on the straight line joining leading and tailing edges). This is illustrated by Figure 5 [17], which indicates that for thin turning vanes of the type shown in Figures 4 (e) and (f) the gap/chord ratio for greatest efficiency is for a ratio of the order of 0.35 while for vanes of thicker section this ratio is greater. The work done by Salter [17] indicates that the efficiency is greatest with the incidence of the leading edge of the vane is between 0° and 5° for both thick and thin vanes.

Since the resistance coefficient is dependent on the gap/chord ratio it would appear that a cascade of annular, axial swirl vanes with a constant gap/chord ratio may have some merit, in order to maintain a small resistance coefficient. Since the gap varies with radius for axial swirl vanes, then so must the chord if the ratio is to be constant. This is illustrated by the variable chord swirl vanes proposed by Mathur and Maccallum [13], those used by Lilley [10] (Figure 6), or the straightener vanes proposed by Collar [2].

Axial swirl vanes are similar to stationary propellers or fan blades in form. They can have a many varieties of cross sections and shape. Some designs have twist, a change in blade angle, from root (I.D.) to tip (O.D.) Helical swirlers are an example of this and are defined by Eqn (2) [1]

$$\tan \alpha = \frac{r}{R} \tan \alpha_o \qquad (2)$$

(Where α_o and R represent respectively blade angle and radius at the outer edge of the swirler, while α and r represent respectively the blade angle at any specific radius). With helical swirlers the blade angle varies with radius.

Swirl vanes may also be designed with straight, flat rather than curved vanes, as illustrated in Figure 7. Flat vane swirlers have blade angles which do not vary with radius, they are constant. Flat blades were used by Mathur & Maccallum [13] and Lilley [10].

Kilik [7], [8] and Gupta et al [5] discuss variations on straight/flat swirlers "2D" curved vane swirlers. The vanes have constant section blades with no twist, constant blade angle. As would be expected, for a given outlet angle, curved vane swirlers produce a larger and stronger recirculation region [7] as well as a stronger swirl. Curved vanes also produce a lower pressure drop [7] than flat vanes. This correlates well in general, to work with turning vanes. Although less efficient, flat vanes are less costly to design and manufacture, and may have additional advantages, such as enhanced mixing [9], in certain applications.

Swirler Performance Data

In Figure 11 are shown relative resistance curves for five different swirlers. All of the swirlers are helical, 30° aerodynamic angle attack at the outer diameter, with the same outer diameter, the same inner diameter, and the same number of vanes, but with different leading edges and chordal variations, these are:

BD1. Blunt leading edge with 0° sweep constant chord (Figure 8)

BD2. Machined leading edge with 0° sweep constant chord (Figure 8)

BD3. Machined leading edge with 75° sweep, tapered outward (Figure 10)

BD4. Machined leading edge with 75° sweep, tapered inward (Figure 9)

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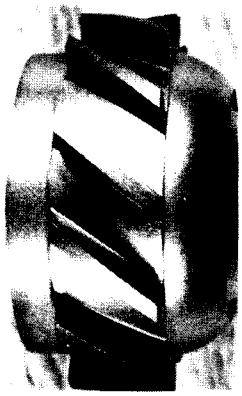


FIGURE 1A HELICAL, AXIAL AIR SWIRLER



FIGURE 1B 2-D CURVED AXIAL AIR VANES

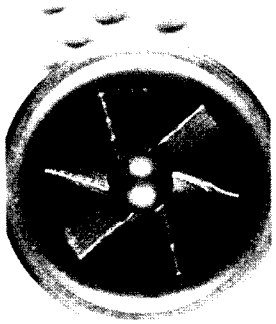


FIGURE 1C STRAIGHT VANE AXIAL AIR SWIRLER

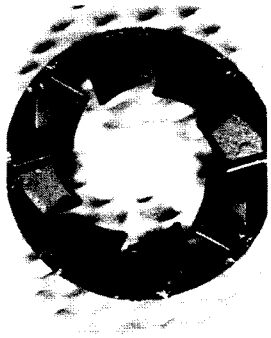


FIGURE 1D CONTOURER STRAIGHT AXIAL VANE AIR SWIRLER

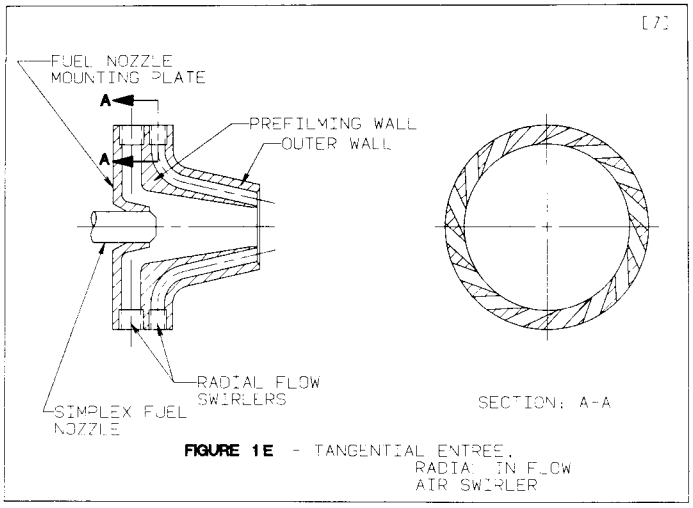


FIGURE 1E - TANGENTIAL ENTRES. RADIAL IN FLOW AIR SWIRLER

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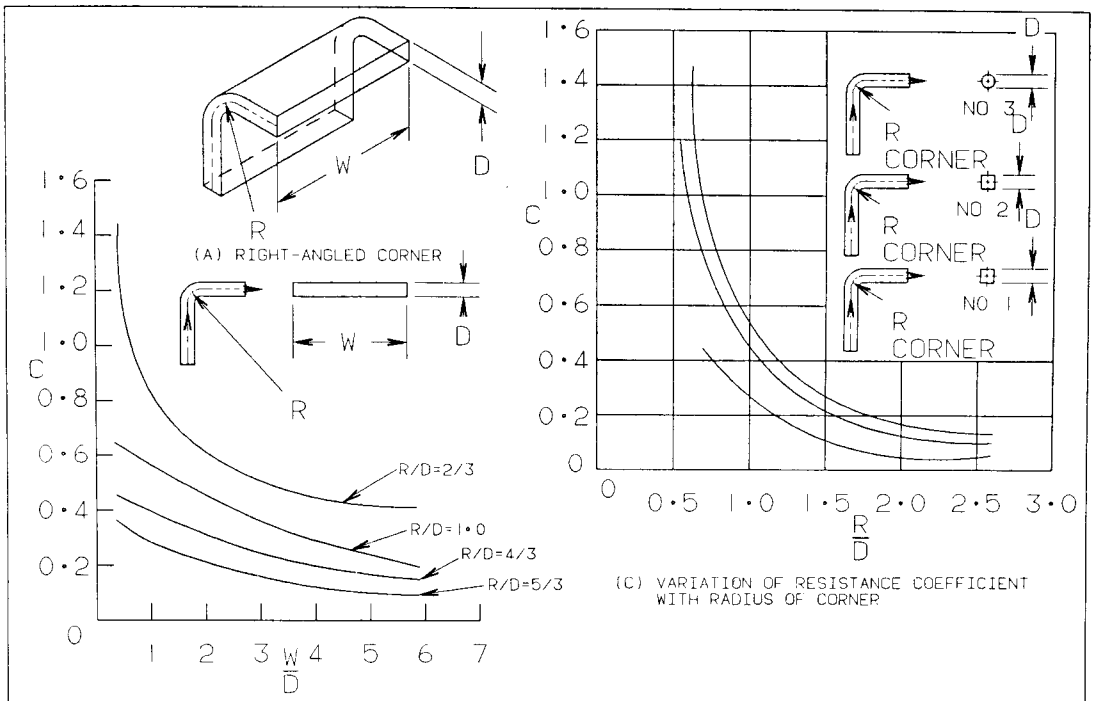


FIGURE 2 - CHARACTERISTICS OF RIGHT ANGLE CORNER

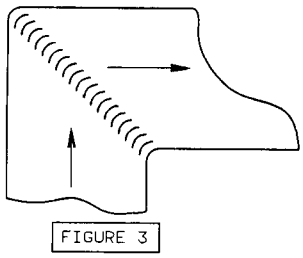


FIGURE 3
TYPICAL VANED CORNER

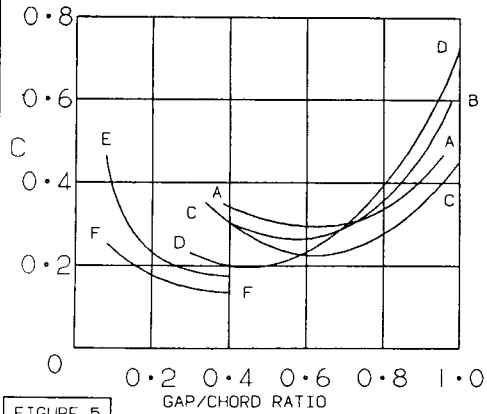
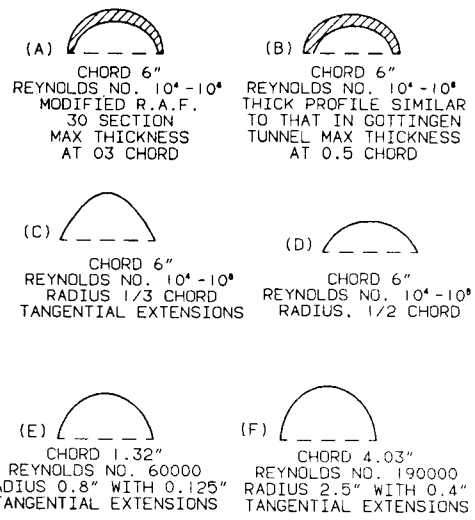


FIGURE 5 - VARIATION OF RESISTANCE COEFFICIENT WITH GAP-CHORD RATIO OF THIN CORNER-VANES.



NOTE: C AND D WERE OF 16 GAUGE SHEET, E OF 24 GAUGE SHEET, F OF 32 GAUGE SHEET. A, B, C, D, WERE TESTED IN A DUCT OF 3'X 1 1/2' SECTION WITH ROUNDED CORNER. E, F, WERE TESTED IN A DUCT OF 1'X 1' SECTION WITH SHARP CORNER.

FIGURE 4 TYPICAL CORNER-VANE SECTIONS

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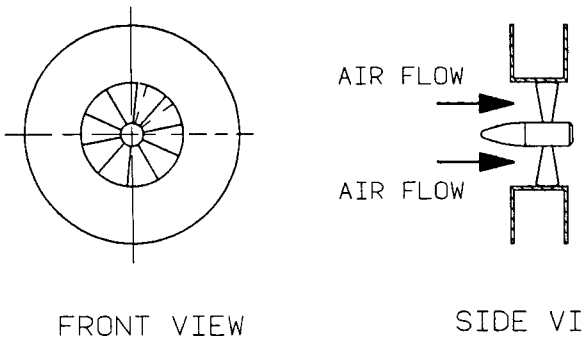


FIGURE 6 DIAGRAM OF SWIRLER - SECTION AND DOWNSTREAM VIEW

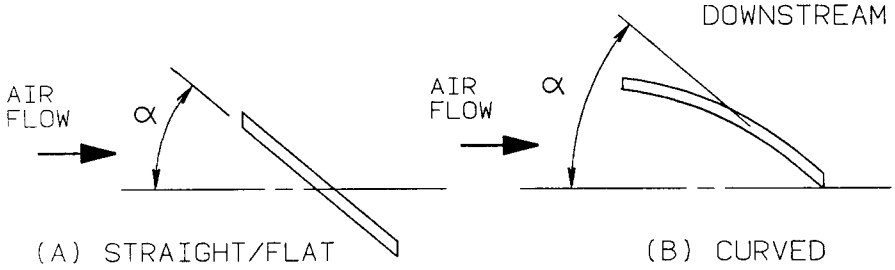


FIGURE 7 END VIEW OF TYPICAL VANES

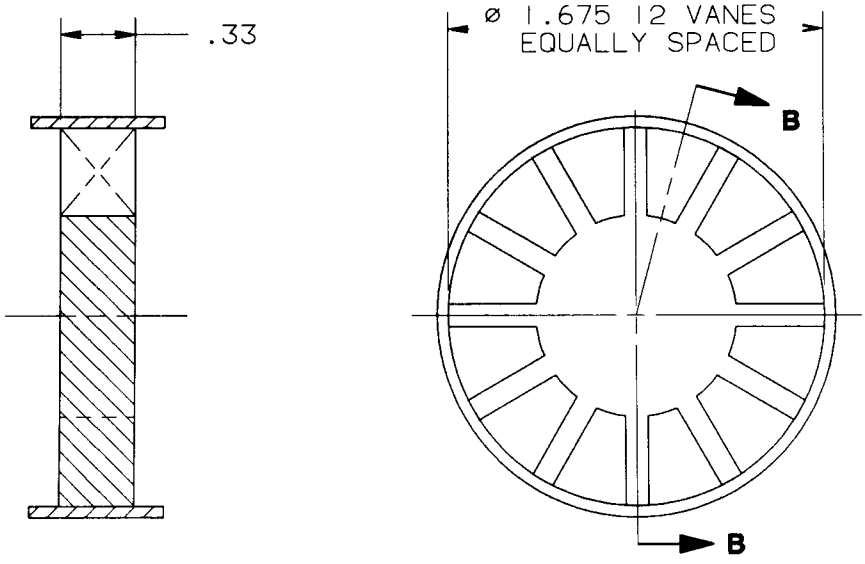


FIGURE 8 CONSTANT CHORD SWIRLER

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BD5. Machined leading edge with 60° sweep, tapered outward (Figure 10) (The machined leading edges are all 30° chisel edges illustrated in Figures 9 & 10)

Figure 12 shows that the relative resistance coefficient can vary considerably for small variations on a particular blade type.

The better performance curves in Figures 11 and 12, lower Ps for a particular flow, , are ordered for the following reasons, starting at the poor and proceeding to the better:

a. BD1 vs. BD2 - A more air foil like leading edge in BD2

b. BD3 vs. BD2 - More outer diameter "flow thru" with BD3

c. BD4 vs. BD2 - More efficient chord/gap ratios with BD4

d. BD5 vs. BD4 - More "flow thru" on outer diameter of BD5

In the fuel nozzle/combustor industry special experimental apparatus is used to measure the constituents of swirl numbers. Using a "swirl strength rig", (Figure 13), the following data were measured for each swirler:

A. The axial force thrust produced by impinging the swirling jet on a flat deflection plate.

B. The swirl reaction torque produced by passing the swirling jet through a hinged, flow straightener.

These data are plotted in both basic form versus pressure drop across the swirler and normalized by flow, in Figures 15 through 18.

In Figure 18 are plotted the swirl numbers based on previous data, using a dimension in the denominator of one.

It should be pointed out that the "swirl strength rig", although used and specified for use, has some difficulties.

1. There is no published correlation of calculated versus measured values.

2. Because of bearing friction; low flow measurements tend to lack repeatability unless great care is taken.

Neglecting the above problems, several things may be pointed out about the resulting data.

1. The thrust vs. pressure drop relationship appears to be fairly linear.

2. The swirl torque vs. pressure drop relationship appears to be linear.

3. The swirl number is more or less constant for pressure drops greater than 0.1 PSID for the swirlers tested.

Terminology

Although much of the terminology used to characterize swirlers and swirling flows is widely used and accepted, it is far from being "standard". Often, two different studies will use very similar terms to describe very different elements. This kind of ambiguity often leads to confusion and contradiction when attempting to compare data from studies of varying flow geometries. In this section, some common terms presently in use will be defined. Following the definitions will be a discussion of the advantages and disadvantages of existing terminology, followed by a list of suggested improvements and standard usage to be adopted by researchers and industries involved in swirling flows.

Swirl Number -The "Intensity" of swirl [19] is usually indicated by the swirl number [1] [5]

$$S = \frac{G_\theta}{G_x R} \quad (3)$$

For a free jet in stagnant surrounds G_x and G_o are constants.

Swirl number is often difficult to measure and/or calculate, therefore, simplifications abound. Go and the velocity term of G_x for example can be predicted with reasonable accuracy. The pressure term, however, is difficult to predict because of its dependence on geometry. According to Beer & Chigier [1], when the swirl number is calculated from input velocity distribution rather than from jet distributions the static pressure may be "omitted" and still provide a good approximation. This modified swirl number [1] then is

$$S' = \frac{G'_\theta}{G_{x'} R} \quad (4)$$

(See G'_x in nomenclature)

Another form [5] rewrites the pressure component in terms of w so that (5)

$$S' = \frac{G'_\theta}{G_{x'} \frac{d}{2}}$$

(See G'_x in nomenclature)

A third form [19], pg. 48, uses a slightly different definition

$$S = \frac{\text{Angular Momentum}}{r_e \ (\text{Axial Momentum})} \quad (6)$$

Which is similar to the definition for S', Eqn (4). r_e is the radius of the combustor exit.

Another version of swirl number [19], pg. 49 is termed "geometric swirl number".

$$S_q = \frac{\pi r_o r_e}{A_t} \left[\frac{\text{Tangential Flow Rate}}{\text{Total Flow Rate}}\right]^2 \quad (7)$$

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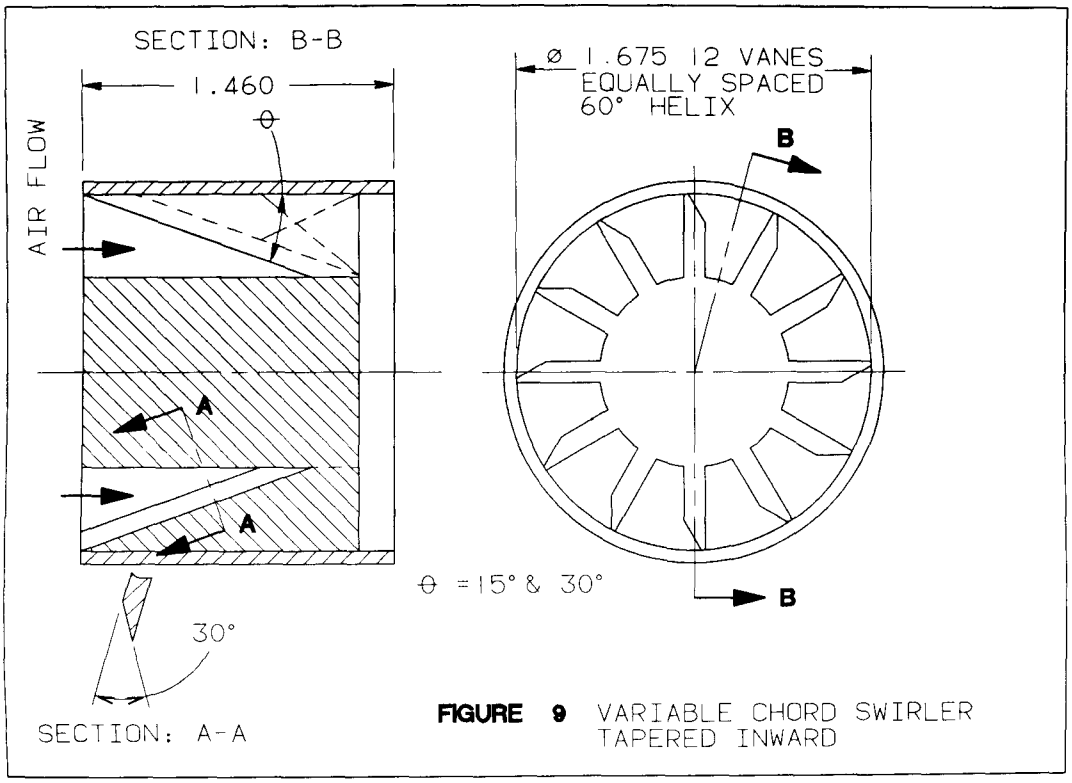


FIGURE 9 VARIABLE CHORD SWIRLER TAPERED INWARD

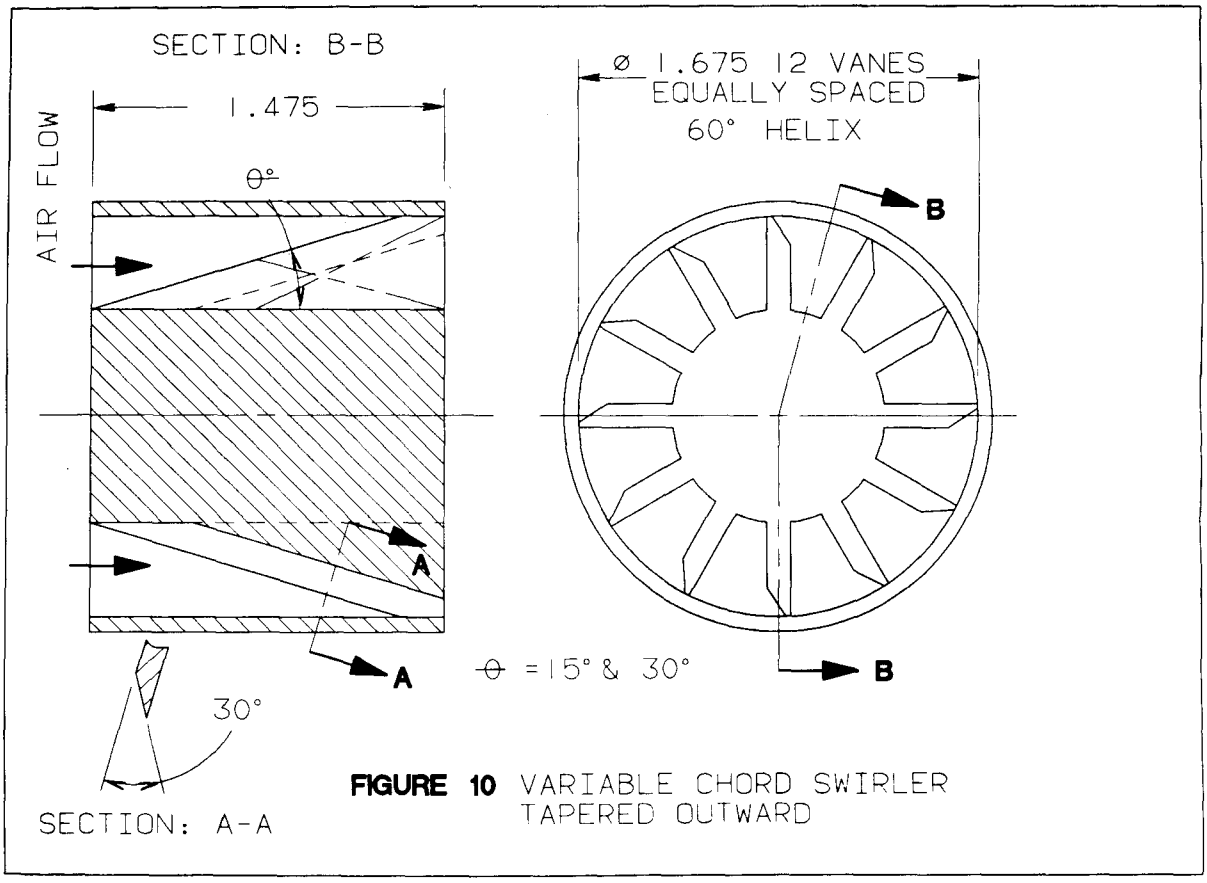


FIGURE 10 VARIABLE CHORD SWIRLER TAPERED OUTWARD

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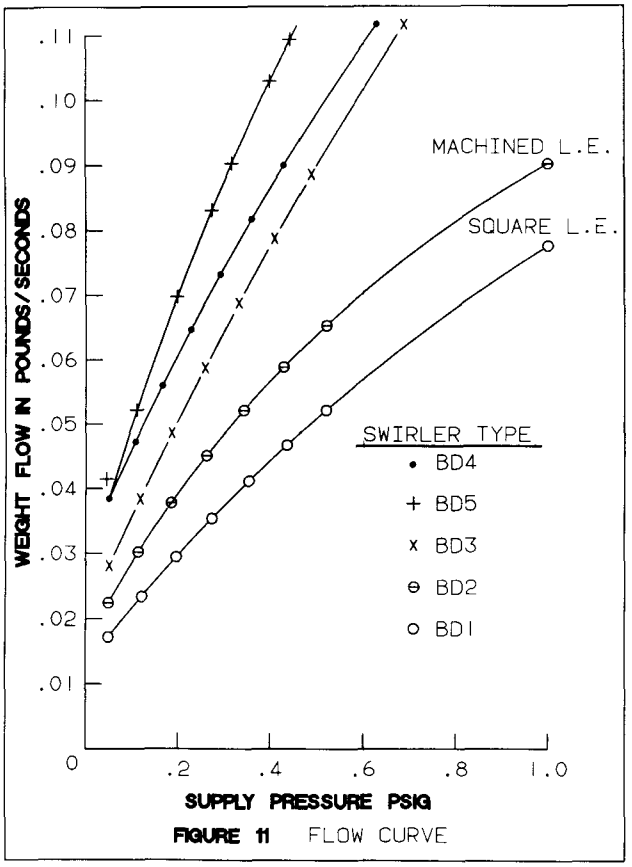


FIGURE 11 FLOW CURVE

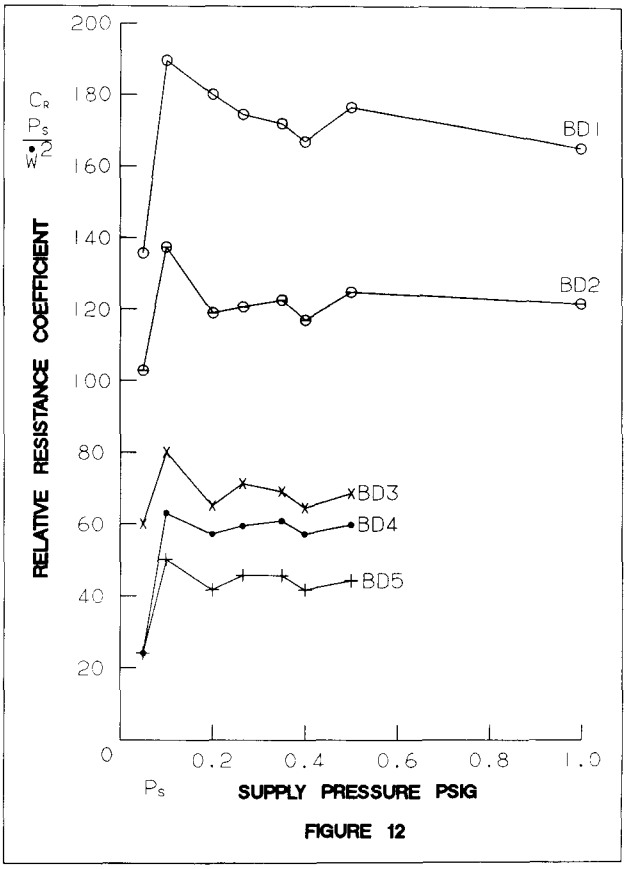


FIGURE 12

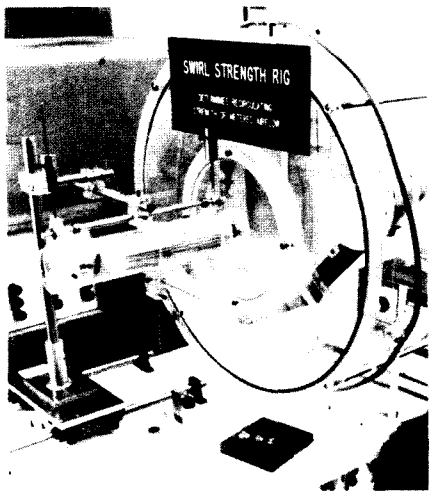


FIGURE 13 SWIRL STRENGTH RIG

The swirl strength rig is used to determine the swirl strength and swirl number of our air assist and airblast nozzles. These important parameters are calculated from the measured values of torque and thrust of the air exiting the nozzle swirler.

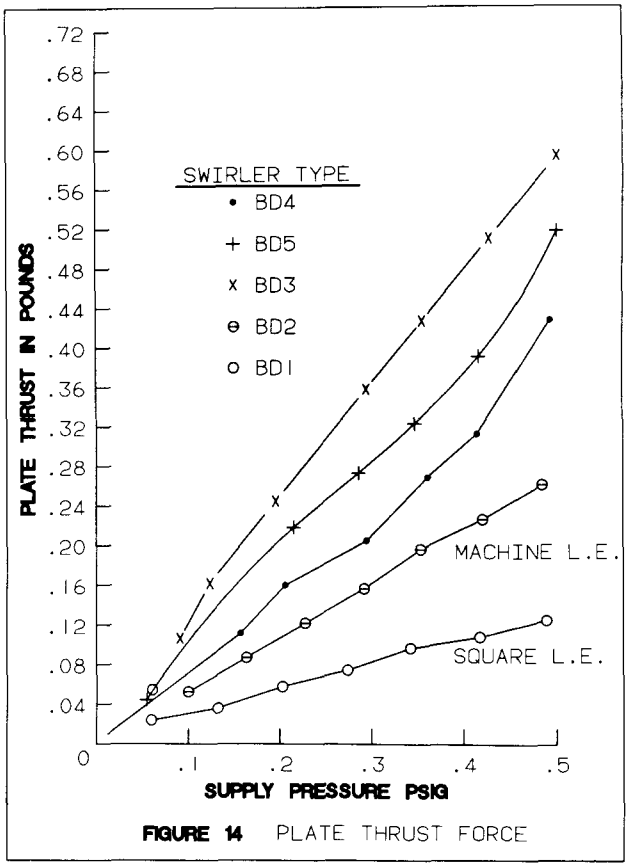


FIGURE 14 PLATE THRUST FORCE

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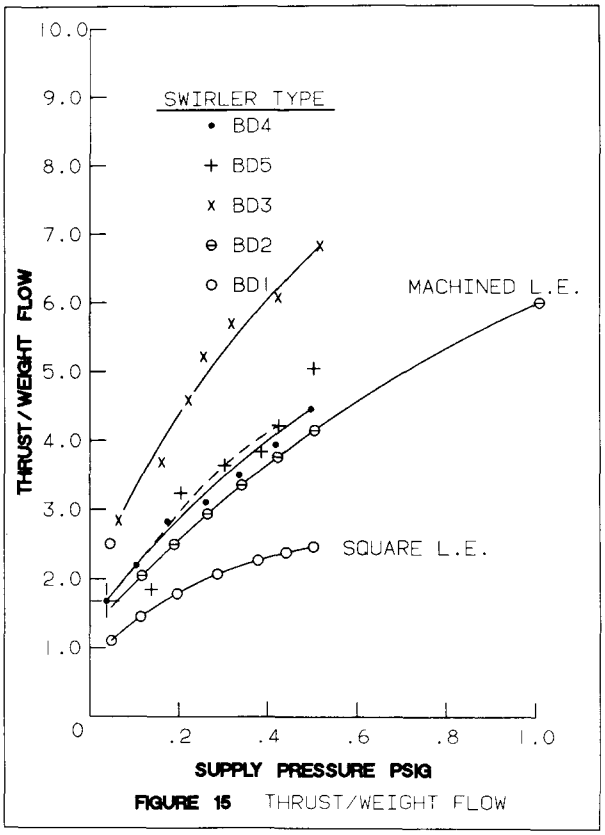


FIGURE 15 THRUST/WEIGHT FLOW

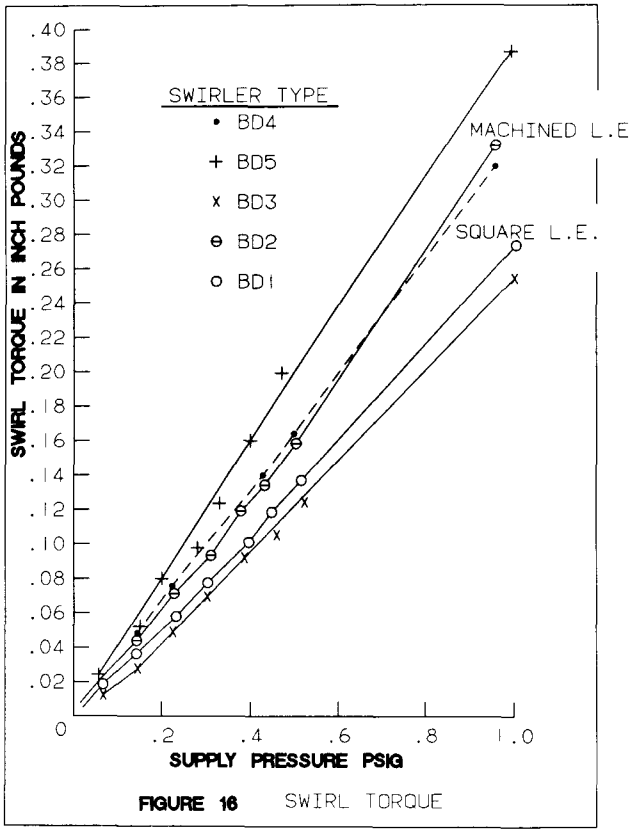


FIGURE 16 SWIRL TORQUE

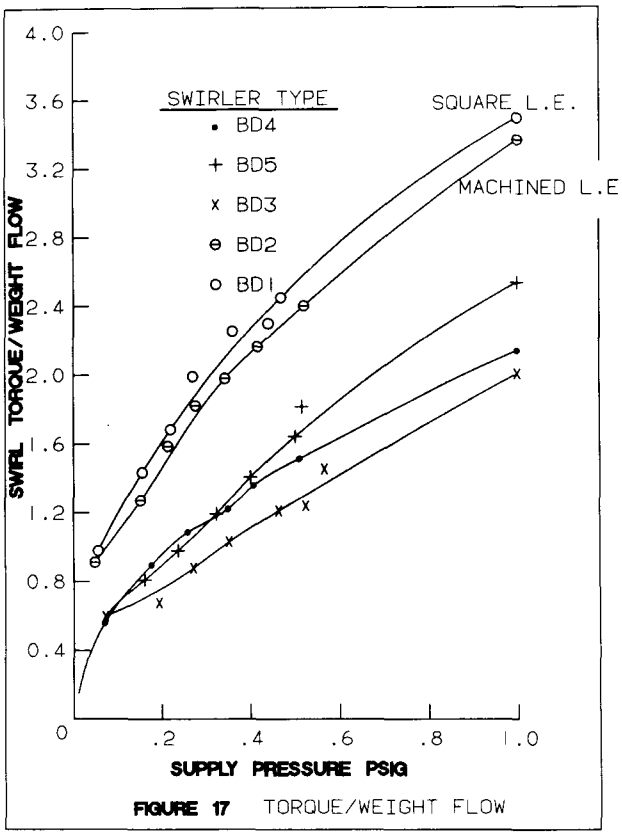


FIGURE 17 TORQUE/WEIGHT FLOW

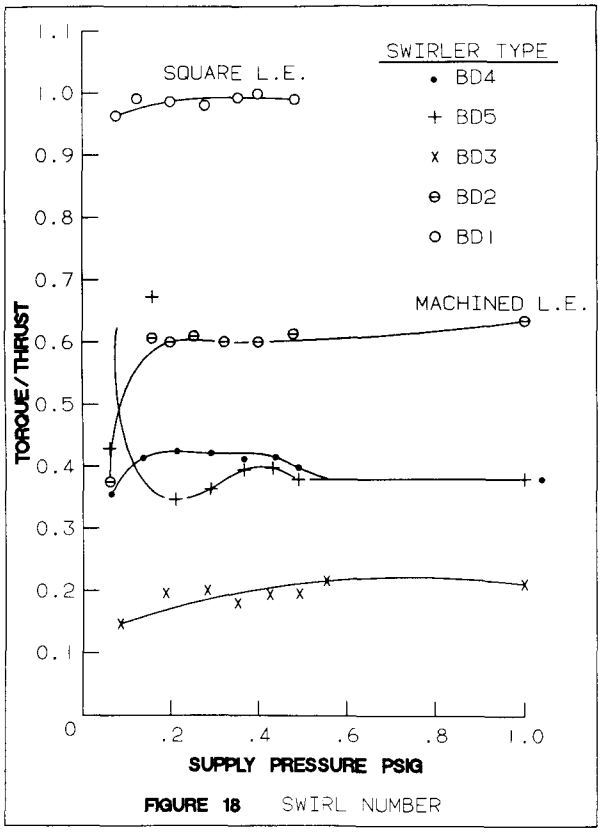


FIGURE 18 SWIRL NUMBER

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Where A_t is the area of tangential holes and r_o their distance from the combustor centerline. The modified swirl number is also referred to as swirl strength. [5].

In addition to at least three different definitions for swirl number in general use Eqn (3), Eqn (4) and Eqn (7), there is no standardization for the "radial dimension", R or d. Some use combustor exit radius, Eqn (4).
Some use the radius of the orifice in which the swirler is placed. Some use diameter.

Swirl Efficiency - Efficiency of swirl generation has been defined in at least two ways. One definition [1] [5] uses the ratio of the flux of kinetic energy of the swirling flow of the swirl generator, divided by the drop to total pressure.

$$E_L = \dot{m}^o \frac{\left[\dot{V}^2 + \delta S^2\right]}{2\Delta P_o} \qquad (8)$$

Where δ is a coefficient dependent on type of swirl, radii ratios, and axial velocity distributions.

A second definition [13] is a ratio of pressure drops

$$E_M = \frac{\Delta P \text{ (Theoretical)}}{\Delta P \text{ (Actual)}} \qquad (9)$$

Blockage Ratio - the ratio of the diameters defining an annular duct.

$$B.R. = \frac{(d)^2}{(D)}$$

d and D are respectively the inner and outer annular swirl diameters [1] [8]. This parameter affects the strength of swirl, and swirler pressure drop for a given outside diameter, according to Kilik. It is also extremely important for bluff- body stabilization.

Blockage Factor [1] - A parameter which accounts for the inlet frontal thickness of swirl blades/vanes.

$$\psi = \frac{\text{(Total frontal area blocked by blade thickness)}}{\text{(Total unblocked swirler inelt area with zero thickness)}} \quad \text{Global Value} \qquad (11)$$

or

$$\psi \simeq \frac{\text{(Projected frontal blade thickness)}}{\text{(Annular Circumference)}}$$

for axial vanes, local value (12)

Solidity - In swirler technology it is most often defined as

$$\sigma = \frac{\text{(Frontal swirl vane projected area)}}{\text{(Total unblocked swirler inlet area with zero thickness)}} + \psi \quad \text{Global Value} \qquad (13)$$

It is used as a measure of "see through" or apparent blockage of the swirl passage. With a solidity of less than one, one can "see through" the swirler. With a solidity of one there is no "see through" but no blade over lap. With values greater than one the vanesvisually overlap.

$$\sigma = N \frac{\text{(Blade chord)}}{\text{(Annular circumference)}} \sin\alpha + \psi \qquad (14)$$

OTHER TERMINOLOGY

Swirl Magnitude - There is no specific term which commonly indicates the magnitude of swirl or the strength of the resulting vortex. This should be easily measured and predicted.

Swirl Rotation - There is no good standard definition of swirl rotational direction (+) or (-). The commonly used clockwise or counter clockwise as viewed from the front or back is ackward.

SUMMARY

For a swirling turbulent jet submerged in a stagnant fluid, the swirl number, at high Reynolds numbers, may be useful as a guide to the similitude of flow patterns in a given geometric volume, in particular recirculation. In a combustor however, the primary zone recirculation is generally established by the primary holes with the swirlers establishing a superimposed swirl. At ignition, flow patterns are perhaps more dominated by the swirl.

Several things may be noted from the plots, presented in this paper.

1. The thrust vs. pressure drop relationships appear to be linear.
2. The swirl torque vs. pressure drop relationship is linear.
3. The individual swirl numbers are constant for pressure drops greater than 0.1 PSID for each of the swirlers tested.
4. The swirl number can vary considerably with only slight variations on a specific swirl blade type.
5. There appears to be no direct correlation between swirl number and relative resistance coefficient, although an inverse one may be suggested.
6. There appears to be a direct correlation between the trend of swirl numbers and the thrust force measured.
7. The resistance coefficient can vary considerably with variations on a specific swirl blade type.
8. The modified swirl number locally can be simplified to be the ratio of velocities.

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Information from allied technology fields such as duct design and wind tunnel design appear to offer trends similar to swirler design trends and should be used as guides in swirler design as well as R & D.

RECOMMENDATIONS

A. Swirl number should be treated in much the same manner as Reynolds number, a dimensionless parameter used for similarity comparisons, not to be added or subtracted to piece together data. Like Reynolds number, the radial "dimension" used should always defined. Swirl numbers cannot be used for similitudes in geometrically dissimilar situations.

B. The recommended moment arm dimension theoretically should be centroidal in nature. This centroid should be that of equivalent force producing the angular torque defined by:

$$R = \frac{2\pi \int_0^R \rho u w^2 dr}{2\pi \int_0^R \rho u w r dr} \qquad (15)$$

From a practical standpoint, alternatives may be the mean swirler radius or the centroid of the swirler flow area.

C. Use the "right hand rule" to indicate swirl direction, where the thumb points in the direction of fluid flow and the direction of curled fingers indicate the direction of positive (+) swirl.

D. Use measured swirl torque to specify "Swirl Strength" or calculate the axial flux of angular momentum G'_0.

E. Use the ratio of Swirl Strength to pressure drop (Figure 17) as an indication of swirler effectiveness. This provides a measure of torque produced for a specific pressure drop.

F. Reassess the definition of Swirl Number in light of ease of calculation and measurement techniques currently used.

CLOSURE

Swirler technology, although much used, is in a state of some disarray due to ill defined terminology. Order and organization are necessary if this area of knowledge is to be utilized to its fullest potential. Useful definitions and terms must be standardized, and developed, if necessary. Useful design data must be accumulated and disseminated. Performance variations with Reynolds number, must be qualified.

It is my hope that this paper has highlighted the need and will prompt useful activity.

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REFERENCE

1. Beer, J.M. & Chigier, N.A.: "Combustion Aerodynamics" John Wiley & Sons N.Y. 1972
2. Collar, A.R.: "Some Experiments with Cascades of Aerofoils", Aeronautical Research Committee Report & Memoranda N. 1768, 1936
3. Collar, A.R.: Cascade Theory and the Design of Fan Straighteners:, Aeronautical Research Committee R&M No. 1885, 1940
4. "Fluid Flow Data Books" Genium Publishing Corp: Schenectady, N.Y. 1984 Section 403
5. Gupta, A.K., Lilley, D.G. & Syred, N.: "Swirl Flows" Abacus Press Kent, U.K. 1984
6. Kilik, E.: "The Influence of Swirl Design Parameters on the Aerodynamics Of The Downstream Recirculation Region" PHD Thesis Cranfield Insitute of Technology 1976
7. Kilik, E." "Better Swirl Generation by Using Curved Vane Swirlers" AIAA - 85-0187. AIAA 23rd Aerospace Sciences Meeting 1985
8. Kilik, E.: "Influence of the Blockage Ratio on the Efficiency of Swirl Generation With Vane Swirlers" AIAA - 85-1103. 21st Joint Proplusion Conference 1985
9. Lefebvre, A.H.: "Gas Turbine Combustion" Hemisphere Publishing Co. N.Y. 1983
10. Lilley, D.G.: "Investigations of Flow Field Found in Typical Combustor Geometries", NASA Contractor Report 3869, Feb. 1985
11. Mair, M.A.: "Design of Fans and Guide Vanes for High-Speed Wind Tunnels" A.R.C., R&D No. 2434, 1944
12. Martin, C.A.: "Leading Edge Vortex Generation and its Application to Twin Fluid Atomization Nozzles" Eng D Dissertation Univ. of Detroit 1982
13. Mathur, M.L. & Maccallum, N.R.L.: "Swirl Air Jets Issuing From Vane Swirlers" J. Inst. Fuel, 1967 No. 316 pp 214-25.
14. Pankhurst, R.C.; and Holder, D.W.: "Wind Tunnel Technique", Pitman & Sons Ltd., London, 1954
15. Paterson, G.N.: "Note on the Design of Corners in Duct Systems", Aeronautical Research Committee R&M No. 1773, 1936
16. Pope, Alan: "Wind Tunnel Testing" John Wiley & Sons, Inc., New York 1953
17. Salter, C.: "Experiments on Thin Turning Vanes", A.R.C. R&M No. 2469, 1946
18. Smith, C.E., Graves C.B.: Roback, R. and Dalessandro, D.D." "Fuel Injector Characterization and Design Methodology to Improve Lean Stability" AIAA 85-1183 21st Joint Propulsion Conference 1985
19. Swift, W.L. Barna, P.S. and Dalton, C. Editors: "Vortex Flows, ASME N.Y. 1980

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