EFFECT OF SWIRL ON PREMIXED COMBUSTION, by F. C. Gouldin and S. Leibovich

Many phenomena, including large scale flow recirculation, are observed in swirling flows. A particularly interesting set of flows, including closed recirculation zones, is often observed at sufficiently high Reynolds number and intermediate swirl levels. First observed in aerodynamic contexts, these phenomena have been referred to as vortex breakdown. The presence of a nearly stationary stagnation point on the axis and unsteady flow in the vortex core downstream of the front stagnation point are common characteristics of vortex breakdown. Experiments reveal a number of possible forms for vortex breakdown. Swirl flow combustors frequently exhibit similar flow features which we regard as additional examples of vortex breakdown. Such flow phenomena include central closed recirculation zones, and the "precessing vortex cores" reported by Syred and Beer.

Swirling flow and vortex breakdown have been studied at Cornell for over a decade. In recent years, attention has been focused on combustion in a premixed swirl combustor composed of confined concentric jets (5 cm and 10 cm diameter). The inner flow is fuel and air; the outer flow is air. Both flows may contain swirl either in the same (co-swirl) or opposite (counter-swirl) directions. The combustor operates at one atmosphere without preheat; methane and propane have been used as fuels. Related analyses and experiments have also been performed for water flows and isothermal air flows. In these studies a number of important concepts regarding premixed/prevaporized, swirl stabilized combustion have been developed. Some of the more significant will be discussed here.

Vortex breakdown exhibits a variety of forms. One of two forms, either the spiral form or the near axi-symmetric ("bubble") form, predominate, depending on inlet and boundary conditions. The occurrence of stagnation points in the vortex core, unsteady flow — usually containing a clear periodic disturbance — and the observed sensitivity to inlet and boundary conditions are all significant to the combustor designer. Not all vortex breakdowns provide a large central recirculation zone, but fortunately such recirculation zones may not be necessary for flame stabilization in premixed/prevaporized systems.

The adverse pressure gradient that can be produced in a vortex flow by dissipation of the swirling velocity component is frequently cited as the agent responsible for flow recirculation in the combustion literature. While adverse pressure gradients are involved in vortex breakdown, in cases of greatest interest they can be traced to kinematic effects in essentially inertia dominated flows, and are not produced by viscosity, or by inherently dissipative effects. The effect of an axial pressure gradient is, of course, magnified on the vortex core centerline by swirl.

Although vortex breakdowns are highly complex phenomena that still defy a completely satisfactory understanding, they have received considerable attention recently, and significant advances have been made. The development of a wave mechanism for breakdown by Squire, Benjamin and by Leibovich and his co-workers has enabled an explanation of many details of vortex breakdown flow. In this picture of vortex breakdown, inertial effects dominate. The wave model of Randall and Leibovich has been successful in predicting some features of the bubble form of vortex breakdown, such as the location and size of the recirculation zone. A major shortcoming of this theory is its restriction to axially symmetric flow. Thus the spiral form of breakdown is not accessible to the

theory. Furthermore, experiments convincingly show that the periodic oscillations present in both spiral and bubble forms of breakdowns are due to waves propagating in azimuth; thus the oscillations also fall outside the scope of an axisymmetric analysis. Oscillations observed in the recirculation zone and downstream sub-critical flow have been traced by Garg and Leibovich to hydrodynamic instabilities. The emerging picture is of an inertia dominated flow sensitive to perturbation. If these perturbations can travel upstream, a vortex breakdown of some form will be present. Flow profiles and boundary conditions determine wave speed and type, hence, the sensitivity noted above.

A variety of experiments have been conducted in our combustor, including visual observations with a sodium tracer, blow-out measurements, and temperature and gas composition measurements throughout the combustor. A primary interest is in NO_x emissions for lean primary mixture operations. Expected reductions in emissions with leaner mixtures are observed. However, quenching of reaction in the mixing layer between the two jets causes reduced combustion efficiency and high CH_4 emissions. Most surprising is the observation of NO_2 in the exhaust. On the basis of these experiments a picture of the combustion process has been developed.

For liquid-fueled, diffusion flame combustors, two popular mechanisms, the stirred reactor recirculation zone model and the boundary layer ignition delay model, have been proposed for flame stabilization. Temperature and composition measurements and emission spectroscopy studies show that reaction is not uniformly distributed throughout the recirculation zone, and the stirred reactor model is therefore not appropriate for our combustor. The observation of reaction upstream of the recirculation zone and of insensitivity of the lean blow-out limits to recirculation zone size are difficult to explain in terms of the ignition delay model. In our combustor we believe that combustion takes place in a thick pre-mixed turbulent flame-like structure. The flame is stabilized in the region of the forward stagnation point of the recirculation zone. Reaction propagates radially from this region while being convected downstream. Upstream convection of products in the recirculation zone is not essential to flame stability.

We believe that combustion in premixed/prevaporized combustors employing a free standing recirculation zone will be similar to what we observe. In these combustors, blow-out will depend on conditions in the forward stagnation region. Efficiency will depend on radial flame propagation. It is the low velocity region of flow upstream of the recirculation zone that makes combustion possible; upstream convection of hot products within the recirculation zone is not essential.

FIGURES

1. Photograph of typical axisymmetric vortex breakdown observed in water flow at approximately 2000 Reynolds number. For flow visualization, red dye is injected on the centerline; blue dye is injected off the centerline. Flow is left to right. The tube diverges slightly as is evident in the picture.

2. Mean Axial Velocity Profiles in Water Flow Containing Axisymmetric Vortex Breakdown as Measured by Laser Doppler Velocimetry. Re = 2560 based on flow rate and tube diameter. Axial positions of profiles are given by their distance from front stagnation point. Positive values denote positions downstream of the front stagnation point.

3. Time Mean Streamlines Inside Axisymmetric Vortex Breakdown for Flow of Figure 2. Note multicellular flow and multiple stagnation points.

4. Low Frequency Components of Energy Spectrum Measured by Laser Doppler Velocimetry at Three Radial Positions in the Recirculation Zone. Conditions are those of Figures 2 and 3. Fluctuations appear to be due to nonaxisymmetric waves.

5. Swirl combustor with pyrex test section in operation under co-swirl conditions (see Table 2). For ignition a continuous discharge spark ignitor is introduced through the port evident in the picture. During probe measurements a similar port in the stainless-steel test section was plugged to prevent flow distortion.

6. Swirl combustor in operation under counter-swirl conditions (see Table 2).

7. Schematic of swirl combustor showing swirl generators and test section. The approximate location of the recirculation zone is indicated. Axial measurement stations are noted by the letters a, b, c, etc.

8. Swirl combustor blow-off limits based on inner flow equivalence ratio for CH_4 firing. The combustion volume is estimated to 1.3 X $10^{-3}m^3$ for all conditions.

9. Radial traverse for high co-swirl case. S_o = 0.559, S_i = 0.523, ϕ_i = 0.79, ϕ_{oa} = 0.25, u_i/u_o = 1.5, u_{oa} ≅ 23.3 m/s.

10. Time mean isotherms (K) for co-swirl (a) and counter-swirl (b) conditions. R_o is the combustor radius and D_o its diameter.

11. Time mean isopleths of CH_4 (ppm) on a dry basis for co-swirl (a) and counter-swirl (b) conditions.

12. Radial profiles of line of sight CH and CO_2^+ emissions from combustor fired on methane (see Table 1). X/D_o = 0.8.

TABLE I.   Combustor Operating Conditions

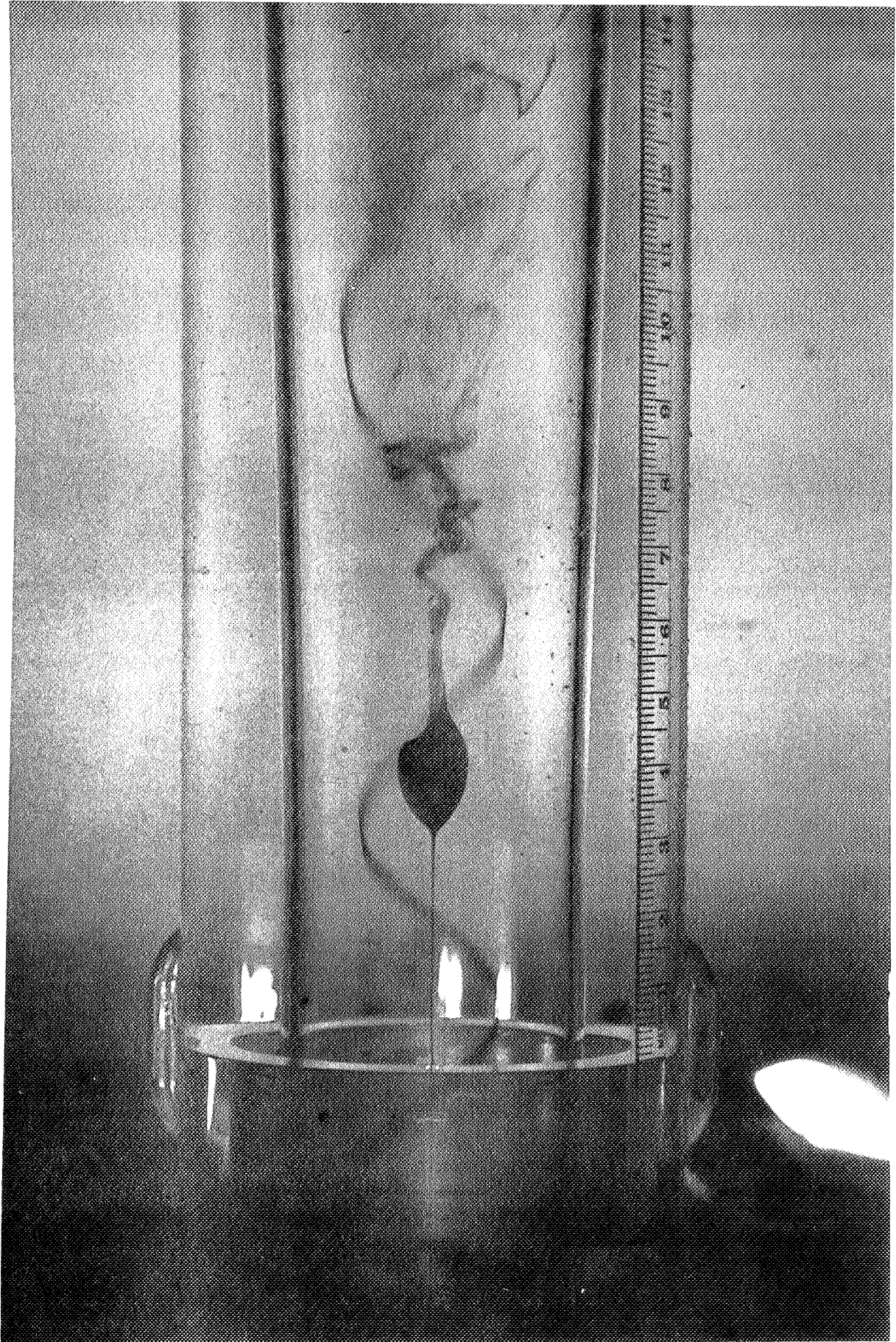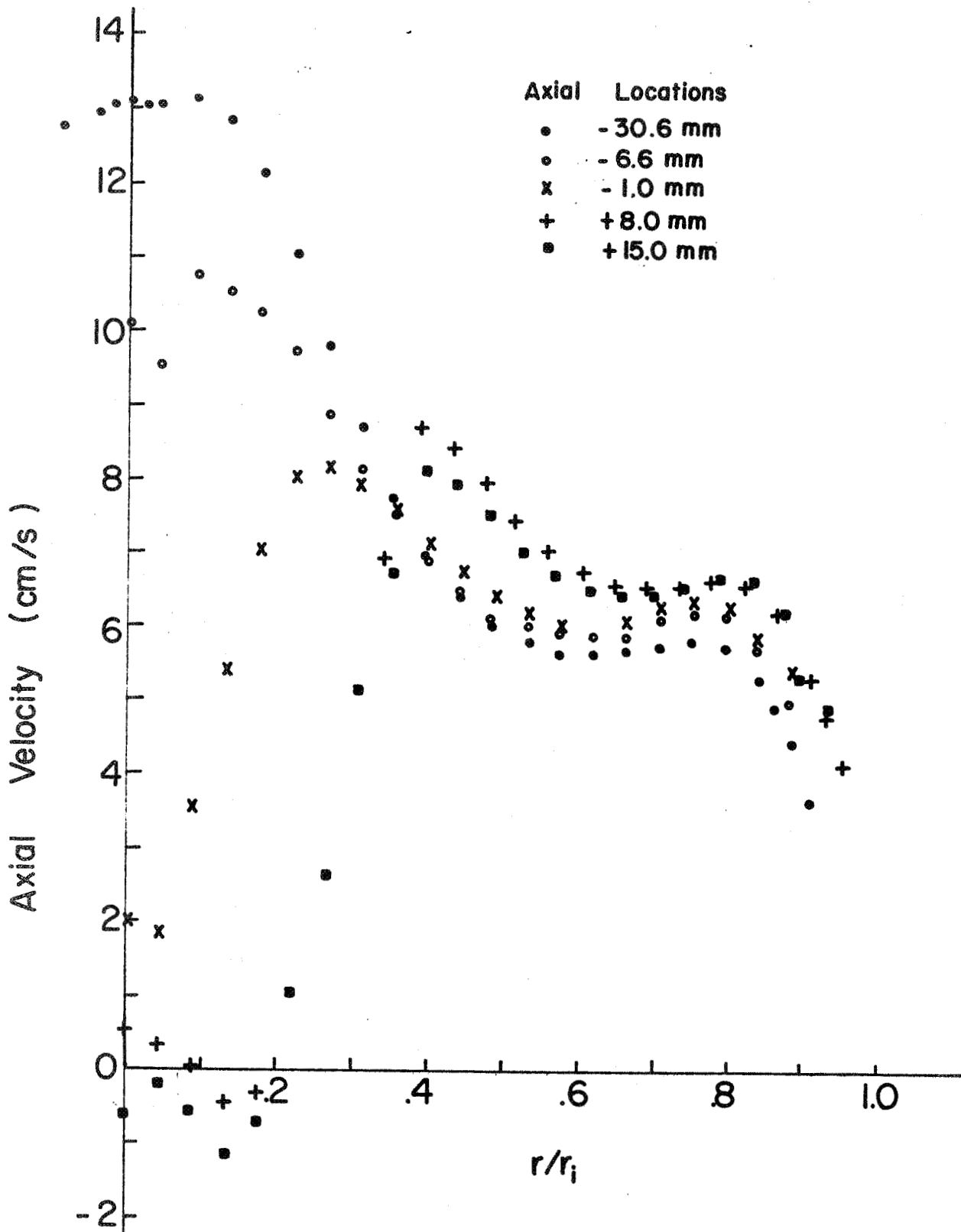|	
inner flow equivalence ratio (ϕ_i):	0.78
overall equivalence ratio (ϕ_{oa}):	0.23
overall average velocity (u_{oa}):	24.6 m/s
ratio of inner flow average velocity to outer flow average velocity:	1.4
inner flow swirl number (S_i):	0.493
outer flow swirl number, (S_o) co-swirl:	0.559
outer flow swirl number, counter-swirl:	-0.559*

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*The minus sign is used to denote the counter-swirl condition, tangential velocities in the opposite direction for the two jet flows. As defined, the swirl number itself is positive.
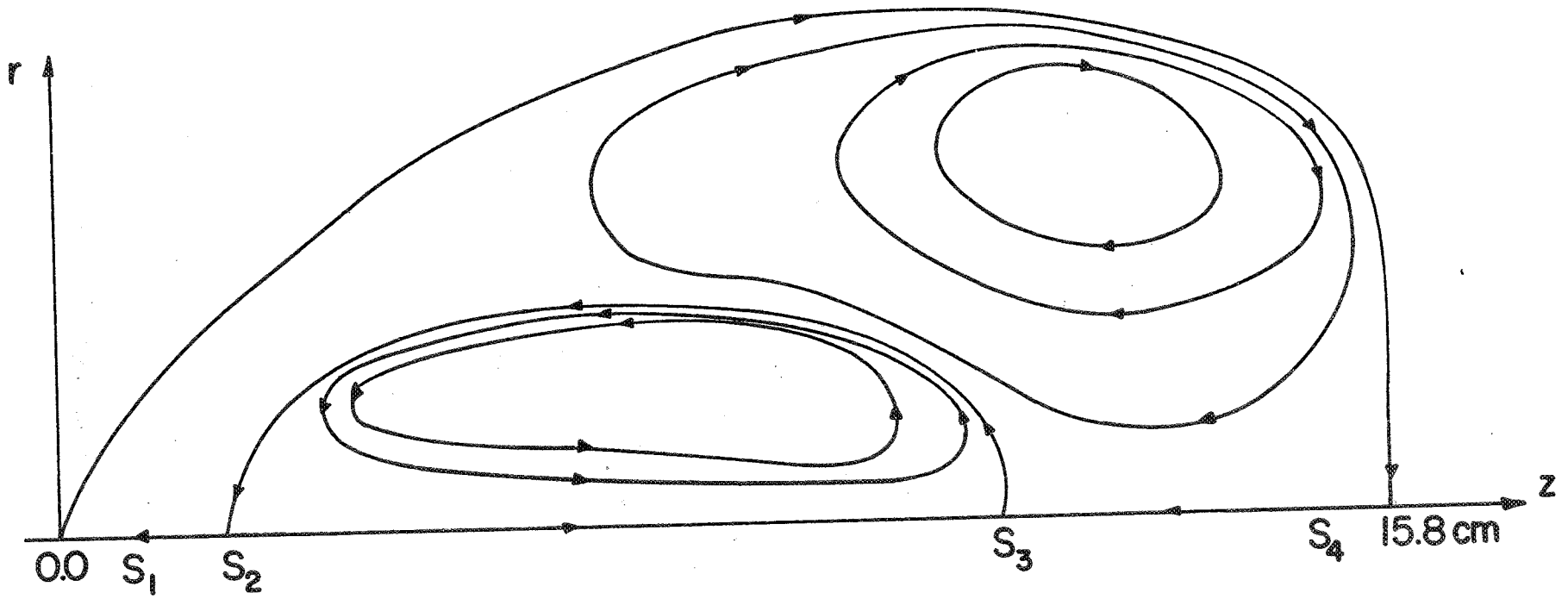
$$S = \int_{R_1}^{R_2} uvr^2 dr \Big/ R_2 \int^{R_2} u^2 rdr.$$ u and v are the axial

and tangential velocities and R_1 and R_2 are the inner and outer radii of the jet in question.

Axial Locations
- -30.6 mm
∘ -6.6 mm
× -1.0 mm
+ +8.0 mm
■ +15.0 mm

Axial Velocity (cm/s)

r/r$_i$

Time Averaged Streamlines

SECONDARY AIR

TEST SECTION

PRIMARY FUEL-AIR MIXTURE

PRIMARY AIR

FUEL

AXIAL INJECTION

TANGENTIAL INJECTION SLOTS

a b c   d   e   f

COMBUSTION ZONE

RECIRCULATION ZONE

SWIRL VANES