Multispark Flow Visualization of Lateral Jet Injection into a Swirling Cross Flow

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Multispark flow visualization experiments have been conducted to characterize the time-mean flowfield of a deflected turbulent jet in a confining cylindrical cross flow. Jet/cross-flow velocity ratios of 2, 4, and 6 were investigated, under cross-flow inlet swirler vane angles of 0 (swirler removed), 45, and 70 deg. The flow visualization results highlight interesting features of the flowfield, as well as the trajectory and spread pattern of the deflected jet.

Nomenclature

D	= test section diameter
d_j	= lateral jet diameter
R	= jet cross-flow velocity ratio, v_j/u_0
u,v,w	= axial, radial, and swirl velocity components
x,r,θ	= axial, radial, and azimuthal coordinates
ϕ	= swirl vane angle

Subscripts

0	= cross flow
j	= lateral jet

Introduction

THE focus of the present study is to present the main characteristics of a deflected turbulent jet entering laterally into confined tubular nonexpanded cross flow that may also possess swirl. This situation occurs in gas turbine and ramjet combustors and the present ongoing experimental research effort is to provide a data base for turbulence model advances used by combustor designers. The specific objective of this investigation was to use a multispark flow visualization technique to highlight the important features of the flowfield. Gross flowfield characterization was obtained for a range of lateral jet/cross-flow velocity ratios $R = v_j/u_0 = 2$, 4, and 6 and a range of inlet swirl strengths in the cross flow, with inlet swirl vane angles of $\phi = 0$ (swirler removed), 45, and 70 deg. The ratio of the cross flow to the lateral jet diameter is $D/d_j = 10$. The experimental test facility, nozzle design, and construction details are given in recent documents.[1-3]

Earlier studies on the flowfield without lateral injection jets have been summarized.[1] Preliminary observations and predictions for the lateral injected jet were given in Ref. 2. A recent report[3] includes flow visualization, multiorientation single hot-wire measurements, and an extensive review of this phenomenon. Recent textbooks review and present the progress that has been made. Schetz[4] concentrates on the physics and modeling of injection and mixing of turbulent flows; Lefebvre[5] acknowledges that the phenomena are of paramount importance in the combustion and dilution zones and presents recent progress and its relevance to combustor design requirements.

Many methods have been used in the manifestation of flowfields; the text by Merzkirch[6] on flow visualization is particularly commendable. Smoke injection, helium bubble injection, and tuft grid methods have been used in earlier studies without any lateral jets.[1] The present study employs a multispark visualization method,[7] from which quantitative velocity deductions are also possible using the method described by Nakayama et al.[8,9]

Multispark Flow Visualization

Flow visualization is used for primary identification and characterization of the flowfield, with three techniques being used in the research program.[2,3] Bubbles, because of their reflective qualities and neutral buoyancy in the airflow, provide an excellent medium to determine the paths of the flow trajectories. Smoke, because of its low comparative density and its tendency to mix well in the flow, makes an excellent medium to follow the flow and to accent the turbulent paths and recirculation zones in the flow. A more novel flow visualization technique employed in these investigations is the multispark method, which is the focus of the present paper.

The spark-gap equipment schematic is shown in Fig. 1. The pulse generating circuit and pulse transformer are manufactured by Sugawara Laboratories, Inc., Tokyo. The equipment is capable of producing pulse trains of up to 200 pulses at frequencies of 1-75 kHz. The output energy of the pulse is 0.05-0.5 J at voltages of 20-250 kV. As used in the present study, the electrodes are placed on opposite sides of the test section, typically one electrode above and one below the test section with a 15 cm spark gap. Approximately 40 sparks are used with 0.5 J/spark at a voltage of 100 kV. Each spark pulse duration is approximately 1 μs; time between pulses is approximately 1 ms.

When a high-voltage source is sparked across an air gap, an ionized path is created. Subsequent sparks will follow the current position of this low-resistance ionized path. By judicious placement of the electrodes in the wall boundary layer, where there is essentially zero velocity (next to wall),

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several discharges can follow the original ionized path as it moves with the fluid. It is necessary to have a low-conductivity test section material (for example, acrylic) so as not to interfere with spark paths. The spark itself provides sufficient lighting for the photographs. One camera (side view) is used for photographs with zero swirl. Two cameras (side and end view) are used simultaneously in the swirl cross-flow cases to give added perspective to the three-dimensional features of the resulting flowfield.

Results and Discussion

Figures 2-4 present spark-gap flow visualization pictures for the cases of $R=2$, 4, and 6, using the method described in the previous section. Parts a-c in the figures correspond to $\phi=0$ (swirler removed), 45, and 70 deg of swirl in the cross flow, respectively. These particular photographs were taken with the electrodes positioned at $x/D=1.50$ where the jet enters at $x/D=1.00$.

In part a of these figures, the camera is positioned to the side of the facility and a vertical rx plane is observed. In the swirl flow cases of parts b and c, a second camera was simultaneously operated from a downstream location to illustrate the $r\theta$ plane behavior of the sparks. In these swirl cases, both photographs have been combined to form a common picture. The respective cases of $R=2$, 4, and 6 with no swirl exhibit the change in the flowfield from $x/D=1.50$ and continuing downstream. The case of $R=2$ shows how the flowfield is merely deflected upward by the entering jet. The lower part of the arcs apparently are deflected around the jet, away from the previously vertical plane, and hence a true three-dimensional effect is perceived in the photograph. The case of $R=4$ shows the flowfield acceleration above and around the jet, which has its centerline nearly corresponding with the centerline of the tube. The "fold-over" just above the jet centerline probably corresponds to the downflow around the jet as the jet displaces the cross flow in the upper half of the test section. The case of $R=6$ shows less uniform behavior. The arcs do appear to define the upper bounds of the jet and the turbulent region behind the jet, as observed in other flow visualization evidence using bubbles and smoke.[2,3]

The swirl flows presented in parts b and c of Figs. 2-4 are actually two photographs taken simultaneously by separate cameras; the two negatives are combined to print a common picture. Again, the electrodes were placed at $x/D=1.50$, with the lateral jet entering at $x/D=1.00$. A wire was placed in the centerline of the tube to prevent the spark from arcing to the tube walls and to help define the tube centerline. The end views exhibit a great deal of reflection off of the inside acrylic tube walls: only the central portion of the view is useful. With moderate swirl ($\phi=45$ deg), the injected jets have little effect on the main flow swirl patterns. However, the $R=6$ case is seen to deflect upward the central core of the swirl flow. The swirl strength seems to be depressed in the lower part of the test section by the additional momentum of the lateral jet. With strong swirl ($\phi=70$ deg), the cases of $R=2$ and 4 seem to slightly inhibit the swirl strength near the outer edge, whereas the $R=6$ case appears to exert its influence more inward in the central region of the flow: swirl

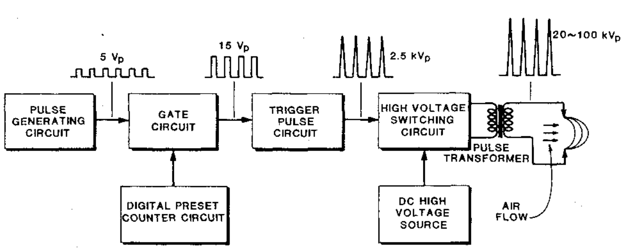
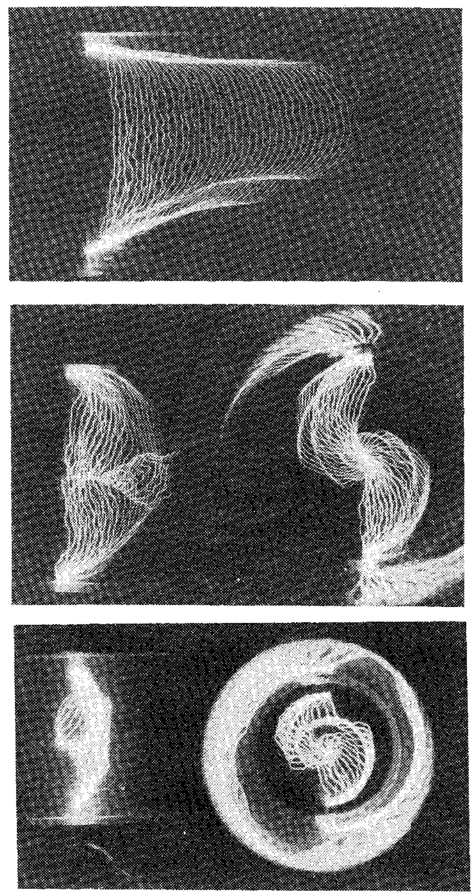


Fig. 1 Spark-gap equipment schematic.

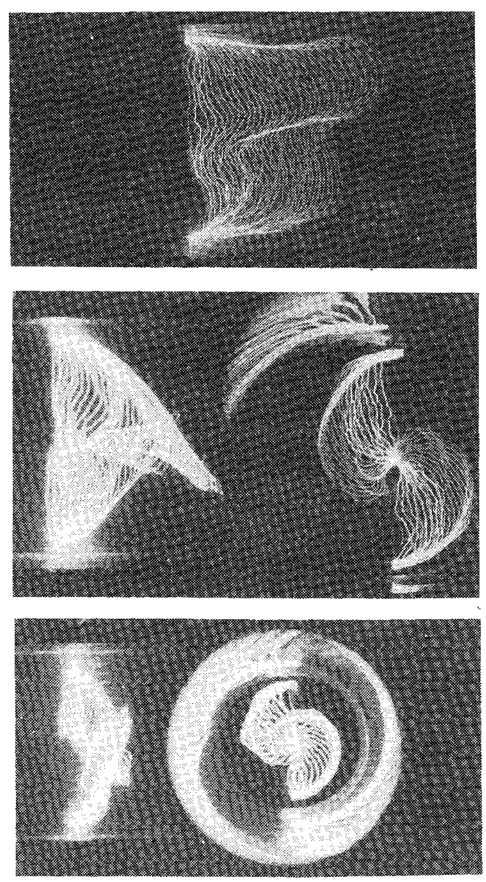


a) $\phi=0$ deg.

b) $\phi=45$ deg.

c) $\phi=70$ deg.

Fig. 2 Spark-gap flow visualization for jet/cross-flow velocity ratio = 2.0.

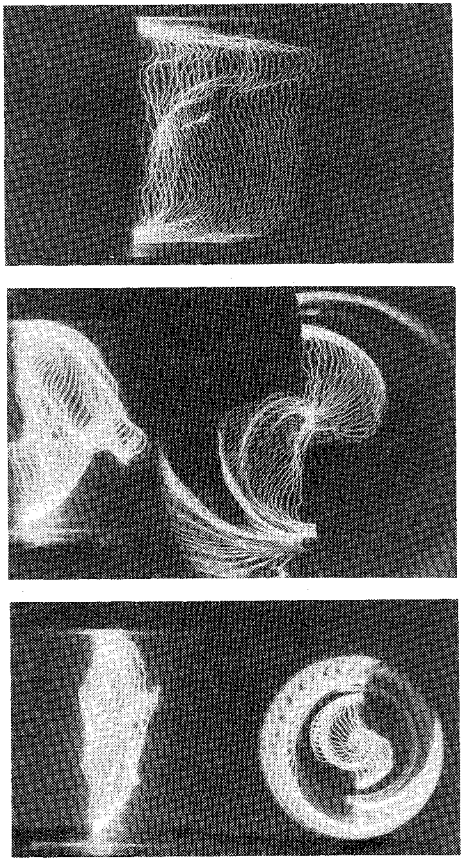


a) $\phi=0$ deg.

b) $\phi=45$ deg.

c) $\phi=70$ deg.

Fig. 3 Spark-gap flow visualization for jet/cross-flow velocity ratio = 4.0



a) $\phi = 0$ deg.

b) $\phi = 45$ deg.

c) $\phi = 70$ deg.

Fig. 4 Spark-gap flow visualization for jet/cross-flow velocity ratio = 6.0

levels in the lower central region are reduced and the central core of the main swirl flow is deflected upward. These results all confirm in general other flow visualization evidence,[3] which leads to a reduced need for detailed experimental measurements.

Conclusion

The multispark flow visualization technique was used to define changes in the flowfield after injection of a lateral jet. The technique demonstrated the bulk effects of range of jet velocity ratios on the main flow, with a range of inlet swirl strengths in the main flow. Multispark photographs taken in the cases with swirl demonstrate the effect of lateral jet momentum of the main flow, including: elevation of the vortex core location, reduction of swirl strength in the lower part of the test section, and extent of mixing and spreading of the jet. In conjunction with other flow visualization evidence, which defines better the lateral jet trajectories, a reduced need for detailed experimental measurements results.

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