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Study of Coherent Structures in Axisymmetric Jets Using an Optical Technique

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Abstract

A NEW optical method using the deflection of laser beams caused by density gradients in the flow is used to study coherent structures in the first six diameters of five axisymmetric jets of different velocities and densities. Quantitative information about the development of coherent structures with axial distance has been deduced and presented in terms of the average interval between successive events and the convection velocity and chances of survival of individual events. The results are found to be consistent with previous published work in this field. The main advantage of this technique is that it can be used to study high-temperature and high-speed flows in which it is impossible to use conventional techniques like hot-wire anemometry.

Contents

The optical system consists of a 4 MW He-Ne laser whose beam is split into five parallel beams all lying in the same plane, which is arranged to coincide with the $Y=0.5\ D$ plane, where D is the nozzle exit diameter. The diameter of each beam is between 1 and 1.5 mm and the distance ϵ between adjacent beams is constant and equal to 7.5 mm. The deflection θ_x of each beam along the flow axial (X) direction is measured by an individual United Detector Technology PIN SC-10 detector. The signals are amplified and then recorded using a FR 1300A Ampex tape recorder. The analysis is done on a Hewlett Packard HP 3721A correlator. The nozzle used is axisymmetric with an exit diameter of 15 mm and is contoured to produce parallel flow at the exit. The study was conducted on five air and CO_2 jets whose details are tabulated in Table 1.

In all of the experiments, the stagnation temperature was equal to the ambient temperature ($\simeq 15°C$) so that the jet fluid was issuing into a fluid of lower density. When a wall of high-density fluid is convected in the X direction with a velocity U_c across a beam, the detector signal V proportional to the deflection θ_x of the beam will show a positive and negative peak corresponding to the front and back edge, respectively, of the wall. Now, consider the covariance $C_{V_1V_2}$ between V_1 and V_2, the deflection signals of beams 1 and 2, respectively, in Fig. 1a. At a time delay τ, it is defined as

$$C_{V_1V_2}(\tau)=\frac{1}{T}\int_0^T V_1(t)\,V_2(t+\tau) \tag{1}$$

where T is the sampling time. To start with, we assume that there is a train of events as in Fig. 1a following one another at an interval Δ and all traveling, without distorting, at a fixed velocity U_c. If Δ is not fixed and the averaging is done over a long time, only the peak at time delay τ_2 given by

$$\tau_2=\epsilon/U_c \tag{2}$$

will survive, since it is due to the same event crossing two beams. The peaks away from τ_2 at intervals of Δ/U_c will progressively decay—the rate of decay being sharper, the less periodic the events. At this stage, we define the correlation coefficient $\gamma_{V_1V_2}$ as

$$\gamma_{V_1V_2}(\tau)=C_{V_1V_2}(\tau)/\sqrt{C_{V_1V_1}(0)\,C_{V_2V_2}(0)} \tag{3}$$

Consider $\gamma_{V_1V_2}(\tau_1)[\gamma_1]$, the correlation coefficient associated with event 1 in Fig. 1a. If the events are strictly periodic, γ_1 will be unity; if Δ is random, γ_1 will be zero. On the other hand, $\gamma_{V_1V_2}(\tau_2)[\gamma_2]$ will always be unity regardless of the periodicity of the events. However, it is known that the events are distorted and also interact continually with each other in a random manner, amalgamating into larger structures as they move downstream.[1,2] Hence γ_2 will decrease with an increase in ϵ and can be interpreted as a measure of the probability that a given structure will retain its identity until a time τ_2, as suggested by Roshko.[3] The other peaks in the correlation

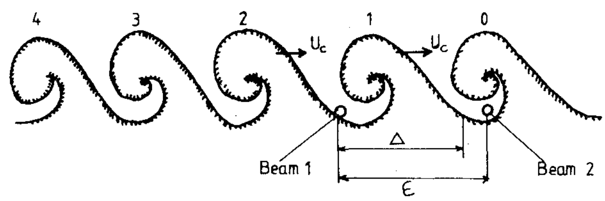

Fig. 1a A simple model for the waves at the jet edge.

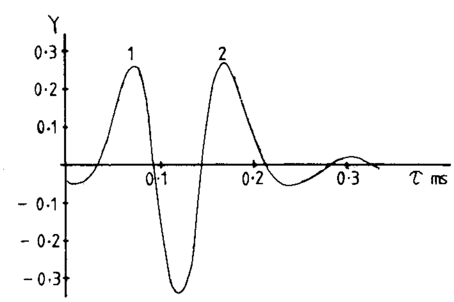

Fig. 1b Typical cross-correlation curve; jet I, $X=0.75\ D$, $\epsilon=1.0\ D$.

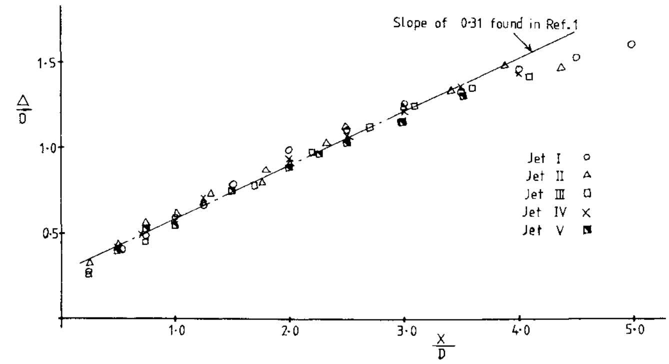

Fig. 2 Variation of average interevent separation with X.

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Table 1 Details of the jets studied (nozzle exit diameter $D = 15$ mm)

Jet no.	Gas	Exit Mach no.	Expected jet temperature, K, assuming total temperature of 288 K	Expected density difference, $\Delta\rho$, kg/m^3	Exit velocity, U_0, m/s	Reynolds no. based on nozzle exit diameter, $\times 10^5$
I	Air	0.44	277	0.0468	148	1.65
II	Air	0.78	256	0.136	251	3.17
III	CO_2	0.56	271	0.736	149	3.18
IV	CO_2	0.27	284	0.674	73.6	1.45
V	CO_2	0.195	287	0.654	53.8	1.04

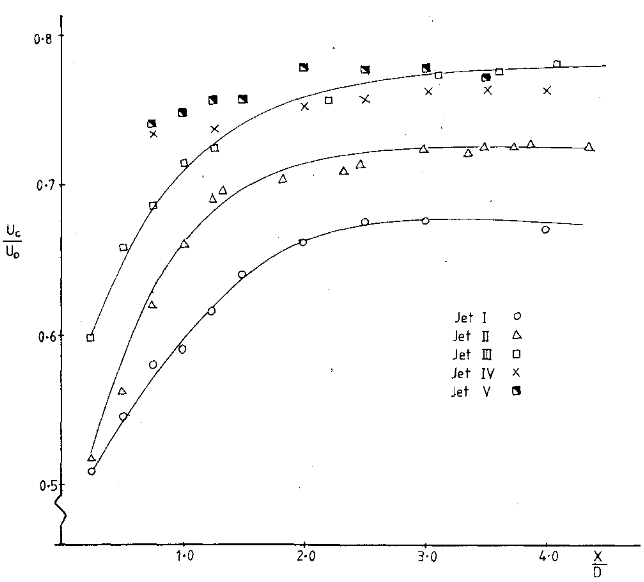

Fig. 3 Variation of convection velocity with X.

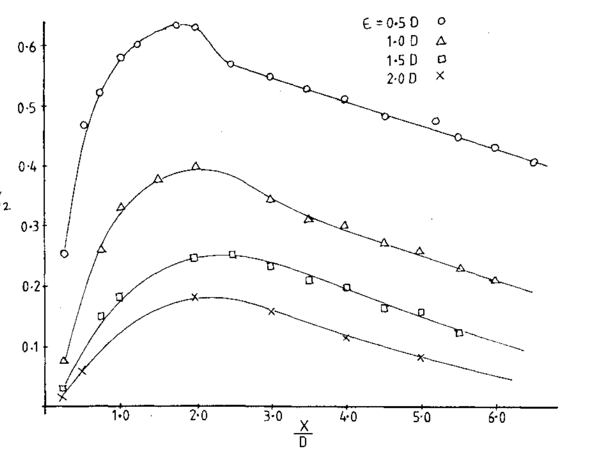

Fig. 4 Variation of a measure of the probability that an event will retain its identity over a distance ϵ with X, jet I.

curve will also be degraded due to this effect. In fact, in most cases considered, only the two peaks corresponding to events 1 and 2 were registered unambiguously, as illustrated in Fig. 1b. We now incorporate in our model the increase in average length scales with downstream distance and write

$$\epsilon = \Delta + (\mathrm{d}\Delta/\mathrm{d}t)\cdot\tau_l + U_c\cdot\tau_l \tag{4}$$

If we choose two values of ϵ for a given value of X and consider the two major peaks in the correlation curves, we get two independent equations corresponding to Eq. (4) and one corresponding to Eq. (1), and we can find the average values of U_c, Δ, and $\mathrm{d}\Delta/\mathrm{d}t$.

In Fig. 2, Δ/D has been plotted against X/D for the five jets studied. Initially, Δ can be seen to increase linearly with X. Moreover, the slope of this straight line is found to be the same as that found by Brown and Roshko[1] for two-dimensional mixing layers and Δ at a given X is comparable for all the jets. In Fig. 3, U_c/U_0, where U_0 is the jet exit velocity, is plotted against X/D. The events appear to start with a low-convection velocity and accelerate over a distance of about 1.5 D, and attain a more or less constant convection velocity. Such a trend has also been observed by others (e.g., Ref. 2). Moreover, it appears that the heavier the jet fluid when compared to the ambient fluid, the nearer the final convection velocity to the jet velocity. Each of the spectra of single beam signals showed a broad-based peak centered at f_p, which satisfied the relation $f_p\cdot\Delta = U_c\cdot f_p$ was found to decrease with X. The variation of γ_2 is illustrated in Fig. 4 where it has been plotted against X/D for jet I. As expected, for a given value of X, γ_2 decreases as ϵ increases. Considering a single plot in Fig. 4, say the one for $\epsilon = 0.5\,D$, it can be seen that an event starting at $X = 0.2\,D$ has a much smaller chance of survival over a distance of 0.5 D compared to an event starting from, say, $X = 2\,D$. Thus, it appears that the number of interactions that are likely to occur between events and the extent of distortion of the events is much higher in the initial part of the jet. Using data presented in figures such as Figs. 2 and 4, we can estimate the distance that event 1 in Fig. 1a has to travel to reach beam 2 and hence γ_l', the value of γ_l expected to be purely due to distortion and interaction of event 1. We now define a parameter α as the ratio of the measured value of γ_l to γ_l'. α may be expected to reflect the periodicity of the events more accurately and we term it as the coherency factor. α was found to decrease from a high value of around 0.6 at $X = 0.25\,D$ to a value of less than 0.1 at $X = 3.0\,D$ for jets I-IV. Moreover, this decrease was found to be sharper in the initial part of any given jet.

The recorded signals were also analyzed using a conditional sampling technique, where the sampling of the downsteam beam signal was triggered by positive peaks in the upstream beam signal. As expected, the peaks in the average conditionally sampled signal occurred at the same time delays as in the corresponding correlation curve. However, in the present case, conditional sampling was not found to be any more sensitive than the correlation analysis in detecting coherent structures.

Thus, it is demonstrated that an optical technique can be employed to obtain quantitative information about coherent structures in axisymmetric jets. Such a technique would be especially useful in the study of combusting flows where hot-wire anemometry cannot be used.

Acknowledgments

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