AIAA JOURNAL
Vol. 36, No. 10, October 1998

Technical Notes

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Duty-Cycle Effects on Penetration of Fully Modulated, Turbulent Jets in Crossflow

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Introduction

THE study of transverse jets in a crossflow is of significant interest and has many practical applications, such as the combustion of a gaseous or liquid fuel jet in a cross flowing air stream, cooling of combustion chamber walls, discharge of chimney gases into the atmosphere, and thrust control. The jet penetration, the entrainment of crossflow fluid into the jet, and the resulting mixing between the two streams are all critical to the efficiency of these processes.[1]

Unsteady injection is one technique to increase the jet penetration and the mixing rate between the jet and the surrounding fluid.[1–3] For example, acoustically excited jet flows exhibit significant increases in jet spread, penetration, and mixing, with changes in the jet structure, compared with unexcited jets.[4] Further, fully modulating the jet, i.e., turning the jet completely off during part of each pulsation cycle, can result in flow characteristics that are quite different from either a steady jet or an acoustically forced jet. Such fully modulated jets can, at low frequencies, penetrate into the crossflow significantly deeper than a steady jet. Experiments with high Reynolds number jets by Eroglu and Breidenthal[1] revealed up to a 100% increase in jet penetration, whereas the flame length of the jet was reduced by 50% at an optimum pulsing frequency. A study by Wu et al.[5] indicated that at low pulsing frequencies a jet injected into a crossflow can penetrate up to four times deeper than a steady jet for the same mean momentum flux. It has also been observed that full modulation of the jet creates distinct vortex rings, whose spacing and strength can change with pulsing frequency for a given jet and crossflow configuration.[1,5,6] The vortex rings formed penetrate deeply into the crossflow due to the self-induced velocity of the rings,[6] often with little change in shape.[2] However, the distance between the sequential rings can decrease as the frequency increases, resulting in increased interaction between the rings and reduced penetration.[1] The details of this interaction in transverse jets, and the implications for penetration and mixing, are not yet well established.

The use of a longer injection time can give rise to pulsed jets consisting of a series of turbulent puffs rather than compact vortex rings. The large-surface area exposed to ambient fluid, combined with the diffuse vorticity of a turbulent jet puff, can give rise to enhanced entrainment and mixing.[7] The rate of mixing is also impacted by the spacing between the individual puffs.[8]

The goal of the current effort is to perform a systematic study of the effects of fully modulated pulsing on the penetration, entrainment, and mixing characteristics of transverse jets in a crossflow. Of particular interest are the specific effects of the pulsing parameters, especially the duty cycle, i.e., the jet-on fraction for each cycle. Research performed in pulsed transverse jets to date has generally been performed by varying the frequency, and therefore the injection time, for a fixed value of the duty cycle (0.5). Controlling the duty cycle as an independent parameter allows the separate specification of the injection time and frequency, with implications for both the structure of jet puffs and the nature of their interaction. This Note describes the initial results of this study using pulsed, nonreacting transverse jets to determine jet penetration for several values of injection time and duty cycle.

Experimental Setup

Experiments were carried out in a recirculating, free-surface water tunnel run at a constant flow velocity of $U_\infty = 15.2$ cm/s. The transverse jet housing was mounted on a false ceiling 59.7 cm in width and 143 cm in length, which was suspended by an aluminum truss 10 cm below the free surface. The leading edge of the 1.3-cm-thick ceiling plate consisted of a 2:1 elliptical section, and the plate terminated in a movable flap 13 cm in length, the position of which could be adjusted to regulate the pressure gradient in the flow. The turbulence intensity in the test section was measured at about 1%.

The transverse jet housing consisted of a circular plenum section 9.5 cm long and 3.8 cm in diameter, to which the 1.3-cm-diam jet fluid supply line was connected. A honeycomb section 3.8 cm in length and a cell size of 3.2 mm separated the plenum section from the nozzle contraction section. The conical contraction section, which extended to the nozzle exit, was 6 cm in length and provided a contraction ratio of 9:1 with an exit diameter of 1.3 cm. The circular jet exit was mounted flush with the surface of the ceiling plate, 25.4 cm downstream of the leading edge of the plate. The calculated laminar boundary-layer thickness at the injection nozzle location was 0.64 cm, less than the jet exit diameter.

Jet fluid was supplied by an pressurized bladder tank at an injection pressure of 138 kPa (gauge), which provided for a jet velocity of $U_j = 98.8$ cm/s under steady injection conditions. This velocity corresponds to a jet Reynolds number of 1.48×10^4 based on the jet nozzle exit diameter and injection conditions. The time-averaged jet flow rate was determined for all cases by collecting jet fluid discharged by the nozzle, removed from the test section, over a fixed time interval. In addition, the jet velocity time history was determined from hot-film-probe measurements over the range of operating frequencies and duty cycles.

The transverse jet flow was pulsed by an in-line solenoid valve mounted upstream of the jet plenum section. A square wave signal of variable frequency and pulse length, generated by a wave generator and amplified by a power supply, was used to pulse the solenoid valve at frequencies of between 0.5 and 10 Hz. The response time of the solenoid valve was approximately 20 ms. The duty cycle α, or fraction of each cycle the jet was on, was programmed in increments of

Received Aug. 26, 1997; revision received July 15, 1998; accepted for publication July 15, 1998.

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one-twelfth, giving values of $\alpha = 0.16$, 0.33, and 0.50. In all cases the jet flow was fully pulsed, that is, 100% modulated. The time-averaged jet flow rate, and hence the mean velocity ratio, in general decreased at a fixed injection pressure as the pulsing frequency increased and/or the injection interval decreased. The response time of the solenoid valve was a limiting factor in choosing operating conditions. For this reason usable data were obtained only for frequencies less than 6 Hz.

Flow visualization was accomplished by premixing the jet fluid supply by a quantity of either red food coloring or fluorescein dye. The jets containing the red dye were backilluminated for direct photography. Sectional views of the jets were obtained by illuminating the jets containing fluorescein dye with a 4-W argon-ion laser beam. The laser beam was spread into a sheet of approximately 60 cm in width using a mirror that oscillated at 1.2 kHz. Images were recorded by a video camera at a standard framing rate of 30 Hz and subsequently digitized to allow the measurement of jet penetration. Jet penetration measurements were made using the food coloring dye. A limited series of runs for flow visualization were made using the fluorescein dye with laser sheet illumination.

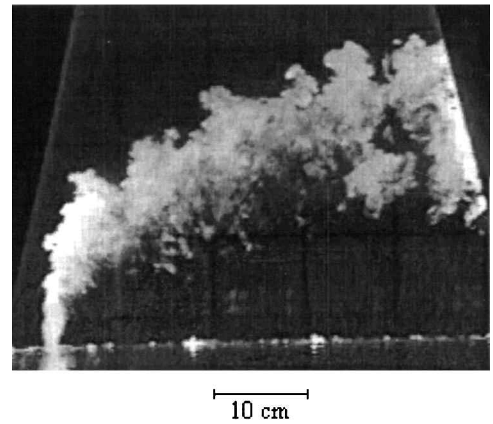
Results

A side view of the steady transverse jet is shown in Fig. 1a for a velocity ratio of $U_j/U_\infty = 6.5$. The direction of the freestream flow is from left to right, and the downstream edge of the image is at the location $x/d \approx 38$ (each square in the background grid is 10 cm on a side). The image shows the interaction between neighboring turbulent structures and vortex loops characteristic of turbulent jet flow.

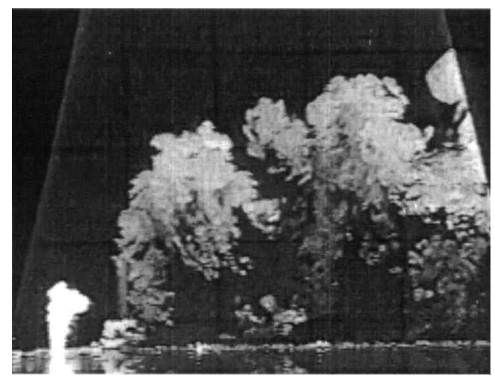
Representative images of transverse jets under pulsed conditions are shown in Figs. 1b and 1c. These images are to the same scale as Fig. 1a. The fully modulated injection conditions can be seen to give rise to discrete puffs of injected fluid in both cases. In the first pulsed case (Fig. 1b), the relatively full duty cycle ($\alpha = \frac{1}{2}$) and relatively long injection time ($\tau_i = 0.5$ s) lead to fairly closely spaced turbulent jet puffs for the injection frequency of 1 Hz. However, there appears to have been no significant puff-to-puff interaction upstream of the location $x/d \approx 20$. Comparable penetration to the steady jet case was observed, even though the time-averaged velocity was significantly less (65.8 cm/s for the pulsed jet vs 98.8 cm/s for the steady case). Note, however, that the average velocity during the injection interval, as determined by dividing the mean velocity by the duty cycle, was somewhat higher for the pulsed jet (131.6 cm/s) compared with the steady jet.

Decreasing the jet injection time, for a given injection frequency, resulted in changes in the jet structure. An example case is shown in Fig. 1c, where the duty cycle was $\alpha = 0.17$ and the injection time was $\tau_i = 0.25$ s, corresponding to a frequency of 0.67 Hz. Two qualitative differences are apparent in this case compared with the fuller duty cycle and longer injection time of the pulsed jet shown in Fig. 1b. First, the lower value of the duty cycle was reflected in a noticeably greater spacing between injected jet puffs. Perhaps more strikingly, the jet puffs were considerably more compact and vortex ringlike. The vortex rings were seen to move into the freestream with little change in their general shape. The emergence of a pair of vortices from each jet puff was due to oscillations in the solenoid valve and the fluid delivery system and is not an intrinsic feature of the pulsed jet flow. Many of the vortex rings generated for short injection times appeared tilted and appeared to move slightly upstream into the crossflow.[2] The penetration of the jet was again comparable to that for the steady jet (Fig. 1a), even though the time-averaged velocity was in this case only $U_j = 27.3$ cm/s. The corresponding peak velocity, defined by dividing the time-averaged velocity by the duty cycle, was 81.9 cm/s. The quantitative changes in jet penetration with frequency and duty cycle are discussed next.

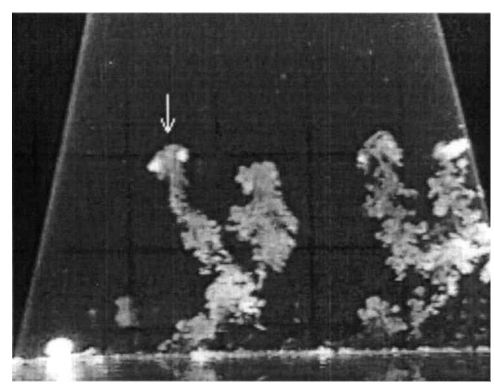
The mean penetration of the jet was determined from the average of a limited number (≈ 10) of individual visual measurements performed at a given downstream location. The uncertainty of the resulting jet penetration values was estimated to be $\pm 5\%$. In all cases in this work, the penetration was defined based on the distance from the wall to the outermost jet/freestream interface, as determined



a) Steady jet



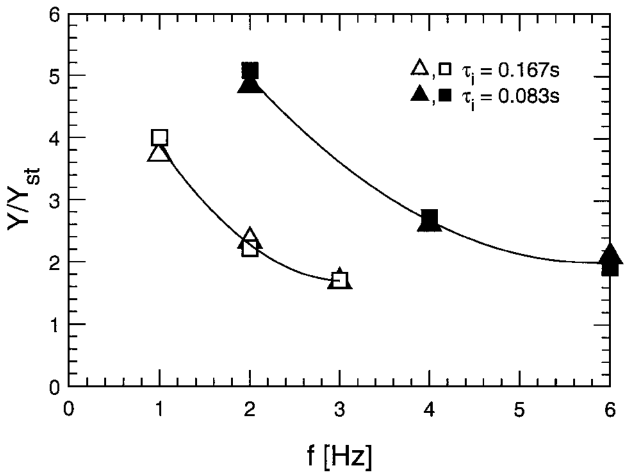
b) Pulsed jet with $f = 1$ Hz and $\alpha = 0.50$



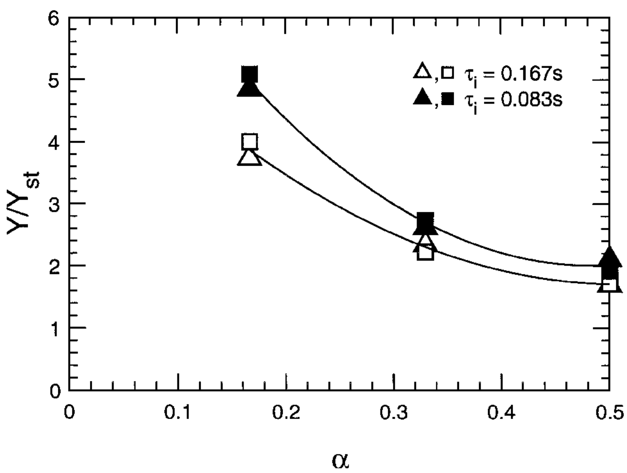
c) Pulsed jet with $f = 0.67$ Hz and $\alpha = 0.17$, where the arrow indicates a vortex ring

Fig. 1 Side-view planar images of transverse jets. The downstream extent of the images is 51 cm.

from the images. Two distinct downstream locations were used for performing the measurements: $x/d = 20$ and 40. To facilitate comparison between pulsed jets with different frequencies and duty cycles, in all cases the average penetration was normalized by the corresponding value expected of the steady jet at the same average velocity ratio using the correlation $Y_{st}/rd = 1.54(x/rd)^{0.32}$, where $r \equiv U_j/U_\infty$ is the time-averaged velocity ratio and Y_{st} is the jet penetration under steady conditions. This correlation was determined from a least-squares fit to the penetration data and is very close to the one-third power fit proposed by Broadwell and Breidenthal.[9] The correlation cited earlier was used to determine the expected steady-state penetration for the velocity ratio corresponding to each specific injection condition. The actual mean measured penetration for each case with pulsed injection, Y, was then normalized by this value.



a) Plotted vs injection times



b) Plotted vs duty cycle

Fig. 2 Normalized jet penetration: △, ▲, *x*/*d* = 20; □, ■, *x*/*d* = 40.

A significant increase in jet penetration, compared to the steady jet with the same mean velocity, was generally observed when the jet was pulsed at low frequencies. This is shown in Fig. 2a for two different injection times. It is important to note that the injection frequency, injection time, and duty cycle are related, i.e., $\alpha = f\tau_i$. Thus, the increase in frequency shown in Fig. 2a implies, for fixed injection time, that the duty cycle also increased. At low pulsing rates, the jet exhibited widely spaced vortex rings. As the injection frequency increased, for a fixed injection time, the normalized penetration dropped as the individual jet puffs became closer spaced in time as the value of the duty cycle increases.

An increase in normalized penetration was also apparent, for a given frequency, as the injection time was decreased. This likely resulted from the injection puffs becoming smaller in size and with more compact vorticity, leading to the higher penetration and lower entrainment characteristic of individual vortex rings. As the pulsing frequency increased, the normalized penetration declined in all cases. However, in no case did the normalized penetration decrease to unity, indicating that a fully modulated jet will always penetrate more than the corresponding steady jet at the same time-averaged velocity. This may be related to the momentum of each pulse being greater than the time-averaged momentum flux of the jet.[1]

Taking two independent variables from the expression $\alpha = f\tau_i$, for example, τ_i and α, suggests that the observed penetration phenomena can be considered to be governed by two separate effects. The injection time can be considered a measure of the intensity of the individual jet puffs, with shorter times generally corresponding to compact vortex rings and longer times to more diffuse, turbulent pufflike structures. Similarly, the duty cycle α can be regarded as a rough measure of the distance between the jet puffs or vortices in the region near the injector. This is related to the observation of Vakili et al.[3] that two separate phenomena affect the behavior of vortex rings: a reduction in vorticity within each ring and a decrease in the distance between the rings as the frequency increases, resulting in interactions between the rings. The utility of using the duty cycle to correlate the penetration results is shown in Fig. 2b, where some collapse of the data from Fig. 2a is apparent. Still, the case with the shorter injection time consistently indicates, for a given value of duty cycle, a somewhat higher normalized penetration than for the longer injection time. This is consistent with the observation by Eroglu and Breidenthal[1] that an additional factor, the spacing of the vortex rings, plays an important role in the penetration depth of the jet. This work extends their results to the case of diffuse, interacting, turbulent jet puffs. The increase in the degree of interaction between neighboring jet fluid puffs with increasing values of α effectively reduces the penetration of the jet into the crossflow.

Summary

A fully modulated turbulent jet in a crossflow was studied by flow visualization over a range of injection times, frequencies, and duty cycles. For short injection times, discrete vortex rings were produced with very high penetration. For longer injection times, more diffuse, puff-like regions of jet fluid vorticity were produced. At a given pulsing frequency, the jet penetration increased significantly as the duty cycle (and the injection time) was decreased and the separation between injected fluid parcels increased. Similarly, the jet penetration decreased with increasing frequency for fixed injection time. These results suggest that the penetration of fully modulated jets in crossflow can be characterized in terms of two independent quantities. The injection time influences the jet structure at injection, with shorter times corresponding to compact vortex rings and longer times to more diffuse, turbulent puff-like structures. The duty cycle impacts the distance between the jet puffs or vortices near the injector, with higher values of duty cycle leading to more intense interaction between turbulent jet puffs and correspondingly less jet penetration.

Acknowledgments

This work was partially supported by the National Science Foundation Research Experiences for Undergraduates (REU) Program. The authors acknowledge the help of Theodore Perrotti in conducting these experiments.

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