Experimental Investigation of the Vortex Street Generated by a Plane Jet in a Counter Flow[1]

R. CURTET.[2] The authors experiments and their results are very interesting, because the problem is original and covers a large field intermediate between wakes and jets. In the first part of the discussion, we would like to recall in which conditions a two-dimensional jet oscillates. In the second part of the discussion, we show how the blockage effect observed by the authors may be represented by a unique parameter, independent from the diameter of the injection cylinder. In the third part, are mentioned some studies on the round jet. We would finally like to cite a recent application of the jet in a counter flow.

1 Oscillating Two-Dimensional Plane Jet. At beginning of our research on confined jets, we have studied [12][3] the behavior of a two-dimensional water plane jet in a parallel flow, confined in a chamber with parallel walls (width $2\ h$). The schematic view of the experimental set-up is given on Fig. 14. The jet exits through a slot of height $2\ a$, which is the end-section of an interchangeable converging nozzle. The ambient fluid also arrives into the chamber through a converging duct. This arrangement was chosen so that the jet and the ambient fluid are parallel to each other when they come into contact, in the entrance section of the mixing duct.

During a first series of tests, corresponding to a given nozzle, we varied the discharge of the ambient fluid in keeping the discharge of the jet constant (discharges per unit width of the ambient fluid $2q_2$, of the jet $2q_1$). In visualizing the fluid particles trajectories with aluminum powder, we observed three flow regimes. Similar experiments were repeated with other conditions: e.g., with other jet flow rates, or nozzle with different exit sections. Our experimental study was performed for positive values of the rate q_2/q_1, as well as for negative values, between 0 and -1. Negative values of q_2/q_1 correspond to a jet flowing into a counter-current.

Fig. 15 shows the three flow regimes observed successively when q_2 decreases for given h/a and q_1. For large values of q_2, the jet diffuses normally into the ambient fluid and all the velocities are from the right to the left (see Fig. 15(a)). For smaller values of q_2, two unequal stationary recirculation eddies appear (Fig. 15(b)). The main eddy extends further upstream as q_2 is decreased. When q_2 becomes smaller, to some critical value, the potential core of the jet begins to oscillate regularly about its mean position. The frequency of the oscillations increases when the ambient discharge decreases. The time evolution of the two recirculating eddies is analogous to the unsteady periodic structure described by the authors in the Introduction.

Similar regimes have been observed for other ratios h/a. The results of the observations are gathered on Fig. 16, which show also the boundaries between the three flow regimes. The curve calculated from the confined jet theory [15, 21] agrees well with the experimental points corresponding to the onset of recirculation.

The frequency n of the oscillating jet has been measured [13] for various values of q_2/q_1 and h/a, and we have shown that the experimental points fall on the curve given by the equation:

$$m^{1/2} - 1.45 = 50\ \frac{nB^2}{Q} \tag{2}$$

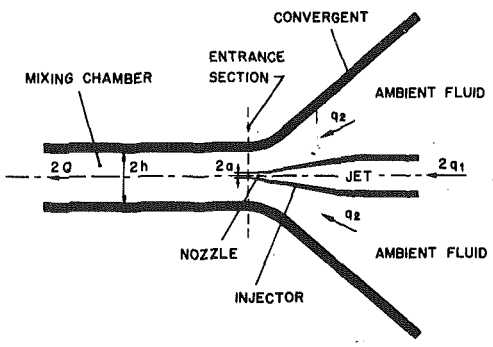

Fig. 14 Experimental set up

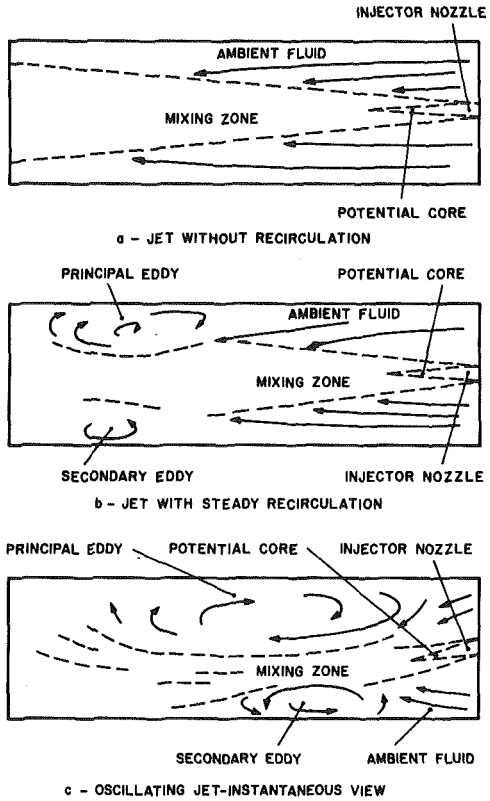

Fig. 15 The three flow regimes in a confined jet

for $m > 2$. The reference width B is defined by:

$$\frac{2h}{B} = 1 + 3.30\ \frac{a}{h} \tag{3}$$

it represents the width of the chamber for small values of a/h. The term $Q = q_1 + q_2$ is half of the total discharge per unit width. Equation (2) shows that the Strouhal number nB^2/Q is directly related to the confined jet impulse parameter m, defined by:

$$m + \frac{1}{2} = \frac{h}{Q^2} \int_0^h \left(\frac{p}{\rho} + u^2 + \overline{u'^2} \right) dy \tag{4}$$

This equation expresses the invariance of the impulse along the chamber, when the friction along the wall can be neglected. In equation (4), y is the ordinate measured from the axis of the jet, u is the local longitudinal mean velocity, u' its fluctuation, p the local static pressure. If there is no head loss in the ambient

[1]By L. Robillard and A. S. Ramamurthy, published in the March, 1974, issue of the JOURNAL OF FLUIDS ENGINEERING, TRANS. ASME, Series I, Vol. 86, No. 1, pp. 43–48.

[2]Maître de Recherches au C.N.R.S., Institut de Mécanique de Grenoble, B.P. 53, 38047, Grenoble-Cedex, France.

[3]Numbers in brackets designate References at end of discussion.

fluid, the static pressure and the ambient velocity u_a, at a given distance x from the nozzle, obey to Bernoulli equation:

$$\frac{p}{\rho} + \frac{u_a^2}{2} = 0 \tag{5}$$

the total head of the ambient fluid being taken equal to zero. The constant 1/2 of the LHM of equation (4) has been introduced so that m equals zero when the jet and the ambient fluid have the same initial velocity.

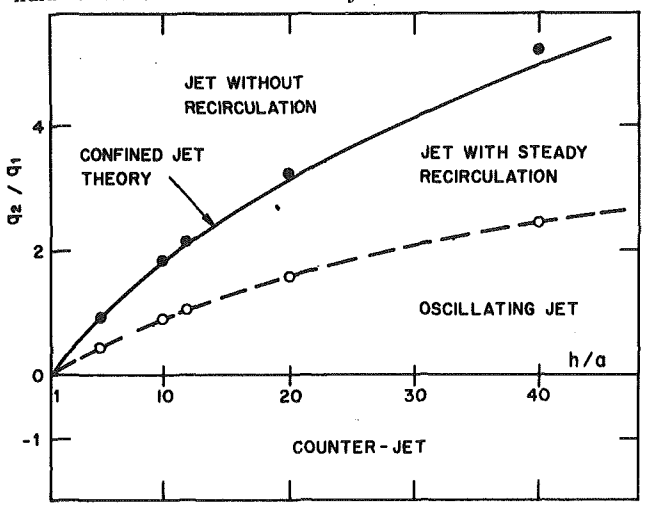

Fig. 16 The frontiers between the flow regimes

An equation similar to equation (4) may be written for a confined axisymmetric jet. From this equation, the impulse parameter $Ct = 1/\sqrt{m}$ given in reference [14] can be derived.

II Blockage Effect. It is possible to reanalyze the results presented by the authors in Fig. 13, specially the blockage effect, in taking into account the arguments developed for the confined jets.

The experimental conditions chosen by the authors allow to simplify considerably the definition of the impulse parameter. They correspond indeed to a very high ratio h/a, larger than 2000. The exit velocity of the jet is, on the other hand, values between 15 and 30 that of the ambient velocity.

In order to simplify the analysis, let us suppose that the velocity distributions in the jet u_1 and in the ambient fluid u_2 are uniform in the exit section; for a counter-jet, the velocity u_2 is negative. The difference:

$$u_e = u_1 - u_2 \tag{6}$$

is the excess velocity u_e and the ratio R_e:

$$R_e = \frac{au_e}{Q} \tag{7}$$

is the relative excess discharge. It can be shown that the integration of the relation (4) in the nozzle exit section leads to:

$$m = -\frac{3}{2} R_e^2 + R_e + \frac{h}{a} R_e^2 \tag{8}$$

But the two first terms of the RMS are negligible small with

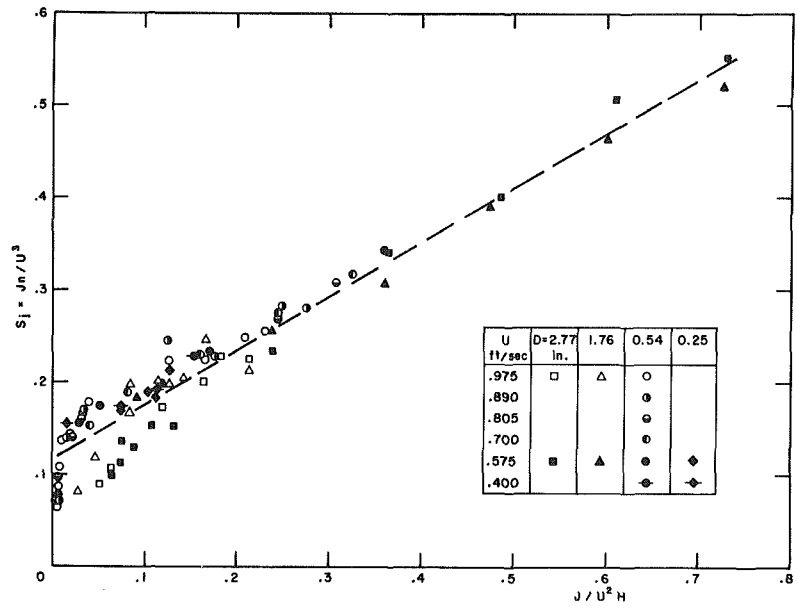

Fig. 17 Experimental points of Robillard and Ramamurthy

Fig. 18 Axisymmetric counter-jet

respect to the third one, in the authors' experimental conditions, so that:

$$m = \frac{h}{a} R_e^2 \tag{9}$$

The excess discharge may for the same reasons be written as:

$$R_e = \frac{a u_1}{h u_2} \tag{10}$$

so that:

$$m = \frac{u_1^2 a}{u_2^2 h} \tag{11}$$

or in the authors notations:

$$m = \frac{J}{U^2 H} \tag{12}$$

Impulse parameter takes here also a very simple form: it is simply the ratio of the momentum of the jet to that of the ambient fluid.

We have replotted the points of Fig. 13 in Fig. 17, in replacing the parameter J/U^2D used by the authors by the parameter J/U^2H defined by equation (12). It is interesting to compare the Figs. 13 and 17, because they are complemental to each other. On one hand, if the Strouhal number S_j is smaller than 0.18, the points collapse on a unique curve in Fig. 13, whereas they are scattered on Fig. 18: the cylinder plays in this case an essential role on the pulsation of the eddies. On the other hand, for large values of the Strouhal number, the branches are spread far apart in Fig. 13, whereas they collapse on a unique curve in Fig. 17. In these conditions, the frequency of the eddies depends mainly on the counter-jet and it is independent of the cylinder diameter. In other words, the periodic motion is essentially controlled in this case by the eddies generated upstream of the cylinder.

III Axisymmetric Jet. Fig. 18 shows a photography of an axisymmetric counter-jet. On this picture, taken from [16], the jet goes from the left to the right and the ambient flow from the right to the left. The trajectories are visualized with small air bubbles. Near the downstream end of the jet, one observes the presence of large eddies, but this eddy system evolves in time without having a clearly defined frequency: this result is in agreement with the works quoted by the authors in their Introduction [6, 7].

However, if the axisymmetric jet diffuses in a swirling ambient flow whose swirl degree is sufficiently high, the jet is entrained by the flow and oscillates regularly about its initial axis. In a recent study on this subject [20], we have shown that the Strouhal number of this periodic motion depends upon the impulse parameter, for a given swirl degree of the ambient flow. One finds thus a result similar to the one which has been obtained for two dimensional plane jets [13, 15].

Oscillations of an axisymmetric free jet may also be generated by other means, specially by mechanical devices creating pulsations of the discharge or of the pressure. We would like to mention here that the following method has been devised in our laboratories for the study of periodic air jets [18, 19]. It consists of two parallel investigations: on one hand, the measurement of the velocity field with a hot-wire anemometer combined with periodic sampling and phase averaging of the signal [18]; on the other hand, visualization of the flow by the schlieren technique and photographs, taken with a very short exposure time (5 μs), giving the time evolution of coherent eddy structures [19].

IV Wall Jet in a Counter Flow. We would finally like to draw the authors attention to an other original application of the counter-jet technique, recently developed by Morkovin, et al. [17]. These authors have shown that injection of fluid in the opposite direction of the main flow, along the wall of a wind tunnel, is a simple way to thicken the boundary layer, and change its mean velocity distribution and turbulent structure. This technique is used in the simulation of the atmospheric boundary layer.

References

12 Curtet, R., "Quelques aspects de l'écoulement dans une trompe à liquides" Comptes-rendus," Académie des Sciences, Paris, Vol. 239, 1954, pp. 387–388.

13 Curtet, R., "Etude expérimentale de la période du jet inducteur dans une trompe a liquides," Comptes-rendus, Academie des Sciences, Paris, Vol. 239, 1954, pp. 472–474.

14 Catchpole, J. P., and Fulford, G., "Dimensionless Groups," *Handbook of Chemistry and Physics*, 49th edition, 1968–1969, The Chemical Rubber Co., Cleveland, Ohio, F. 267, Table B, Serial No. C 12.

15 Curtet, R., "Confined Jets and Recirculation Phenomena," *Combustion and Flame*, London, Vol. 2, No. 4, Dec. 1958, pp. 383–411.

16 Barchilon, M., "Contribution à l'étude des courants de retour engendrés par un jet confine," Publications Scientifiques et Techniques du Ministère de l'Air, Paris, 1969, No. 442.

17 Morkovin, M. V., Nagib, H. M., and Yung, J. T., "On Modeling of Atmospheric Surface Layers by the Counter-Jets Technique-Preliminary Results," Illinois Institute of Technology, Chicago, Ill. 60616, IIT Themis Tech. Report R 72-7, Oct. 1972.

18 Binder, G., and Favre-Marinet, M., "Mixing Improvement in Pulsating Turbulent Jets," *Proceedings of the Fluid Mechanics of Mixing*, ASME, New York, June 1973, pp. 167–172.

19 Curtet, R., and Girard, J. P., "Visualization of a Pulsating Jet," *Proceedings of the Fluid Mechanics of Mixing*, ASME, New York, June 1973, pp. 173–180.

20 Curtet, R., and Martins, B., "Oscillations of a Jet in a Rotating Fluid," Symposium IUTAM/IAHR on Flow-Induced Structural Vibrations, Karlsruhe, Aug. 1972 and Springer-Verlag, Berlin, 1973.

21 Curtet, R., "Jet Flow Between Walls," Rep. RSIC-461, Redstone Scientific Information Center, Army Missile Command, Sept. 1965. (Available from DDC as AD-473 568 L).

Authors' Closure

In this discussion Curtet depicts a general view of jets in confined streams and provides a good insight about the possible extension of the present problem.

Our study related to the counterjet, is a very particular situation of this class of experiments. Specifically, the following conditions were present in the counterjet experiments.

(*a*) The ratio of a/h was extremely small.

(*b*) The size of the injection device D was large, compared to the jet slot and consequently influenced the flow behavior and the frequency of jet oscillation. This effect was taken into account by the use of the parameter involving the size of the injecting device.

(*c*) The jet was opposed to the stream and communication was ensured between the two rows of vortices because the jet was fed from the sides.

The representation of our experimental results provided in Fig. 17 by Curtet is an alternate form of data representation. However, an identical graph was included in an earlier publication.[4] As a matter of fact, it was also observed earlier that the data branch out into three distinct groups depending on the D/H ratio in the low range of J/U^2H (i.e. low blockage). Fig. 19 is reproduced from footnote 4 to indicate this effect.

[4]Luc Robillard, "Contribution à l'étude des jets à contrecourant," DSc thesis Université Laval, Québec, Mai 74.