JET CONTROL BY COUNTERFLOW

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ABSTRACT
The expansion of axisymmetric jets and their initial turbulence level are considerably enhanced by using a suction collar of sufficient length around the nozzle and by producing a counterflow near the jet exit. Visualizations and velocity-fluctuations spectra show that the near-field of the jet is the seat of low-frequency large-size ejections. The observed phenomena seem to be due to a large positive pressure gradient and to recirculation generated by the suction in the collar chamber.

AIM OF RESEARCH
The aim of the present research is to extend the possibilities of controlling turbulent activity and mixing in axisymmetric jets by applying a new technique first proposed by Strykowski's team (Strykowski and Wilcoxon, 1993). In this technique, a countercurrent flow is produced near the jet exit in order to enhance the initial instabilities of the jet ; the results seem very promising for applications to combustion (Lourenco et al, 1996). Strykowski and Wilcoxon (1993, denoted SW herafter) have shown that the initial jet turbulent activity and diffusion are strongly increased by the counterflow. They also observed global oscillations in the first jet diameters and interpreted the flow field development as the result of self-excitation in the jet.

In the present research, we have tested the influence of the initial conditions on the process efficiency and we have adressed the issue of the physical phenomena which occur in this flow.

EXPERIMENTAL SET-UP AND INSTRUMENTATION
The jet nozzle (diameter D1= 20 mm, bulk velocity : U1) is supplied by air from a settling chamber followed by a tube 135 mm long (Fig 1 ; more detailed informations can be found in Boguslawski et al, 1999). A countercurrent flow is created in a co-annular slot of width e (= 3.5 mm) connected to a vacuum pump. This counterflow is characterized by the bulk velocity U2 in the slot.

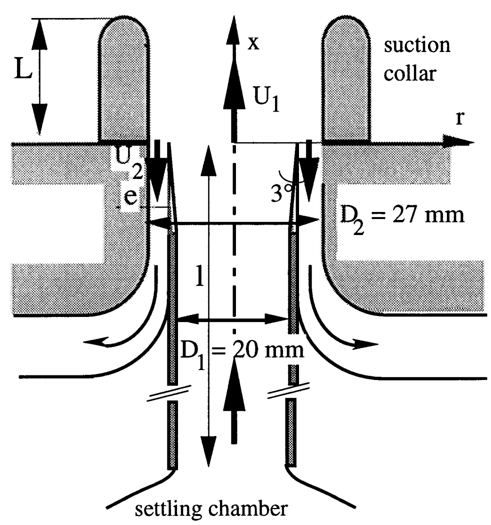

Fig.1 - Sketch of the nozzle with counterflow

The aspirated air flow goes through a vessel of volume 13.5 10^{-3} m^3, located between the nozzle and the vacuum pump. This device is efficient to damp the pressure fluctuations due to the pump. An important part of the set-up is a suction collar (Length L), placed at the nozzle exit in order to form a cavity of diameter D2 (= D1 + 2e = 27 mm). It is aimed at producing a counterflow of significant velocity in the first jet diameter. The present set-up is similar to that of SW, but presents three main differences with it :

i) the slot is narrower in our experiment (e/D1 = 0.175 instead of 0.5).

ii) the suction collar has a constant section (in SW, it is slightly diverging : half-angle 7 deg).

iii) the nozzle follows a cylindrical tube of length l (l/D1 = 6.75) and the jet exit profile corresponds to a central flow of uniform velocity surrounded by developing laminar boundary layers.

The measurements were performed by hot-wire anemometry (diameter 5 µm, CTA anemometer AALAB-AN-1003). Laser-sheet visualizations were performed by using a 15 W copper-laser pulsed at 10 kHz. The jet was seeded with incense smoke.

RESULTS

Hot-wire measurements

The present results were obtained with a suction collar of length 20 mm (L/D1 = 1). The bulk velocity U1 was kept constant at 6 m/s (Reynolds number = 8000), whereas the suction ratio -U2/U1 was varied. The x-axis origin is at the central nozzle exit.

We have checked the jet characteristics without counterflow. The results are the same with and without the suction collar and moreover, are in very good agreement with those of the literature. On the other hand, counterflow effects are very weak on the jet development when there is no collar at the nozzle exit.

Jet diffusion is increased when a collar is placed at the jet exit and suction is applied in the slot at once.

Figure 2 shows the jet exit conditions in the presence of the collar. It was difficult to perform measurements closer from the walls without risking probe damage. The three extreme points on each side of the velocity profile are located in the region of supposed counterflow. Consequently, the corresponding hot-wire signal mean values have been replaced by their opposite in the case of suction.

Without suction, the turbulent intensity is 0.2 % in the central region and reaches a maximum value of 8.3 % in the shear layers. When strong suction is applied (-U2/U1 = 0.36), the corresponding values are respectively 2.2% and 22%. There is therefore a significant effect of suction already near the nozzle exit.

Figure 3 shows the downstream evolution of the jet-axis mean velocity U(x) normalized with its value at the nozzle exit, denoted U1max. The influence of the counterflow is striking : after a transition region, U1max/U(x) varies along a straight line of slope m which increases strongly when the suction ratio is increased. Moreover, this linear regime is reached very close to the nozzle in the case of strong suction.

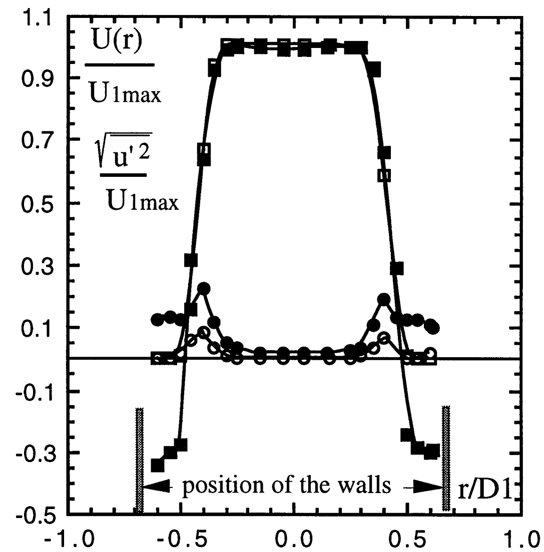

Fig.2.- Mean and r.m.s velocity profiles near the nozzle exit. x/D1 = 0.25. Open symbols : jet without counterflow ; solid symbols : -U2/U1 = 0.36. Squares : Mean velocity ; circles : turbulence intensity

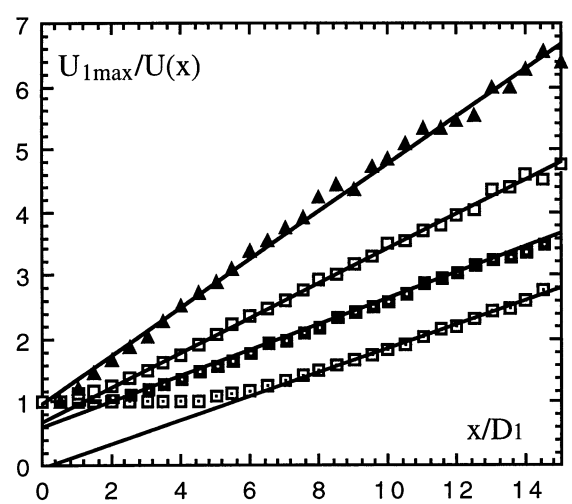

Fig.3- Axial mean velocity profiles.
◘ without suction ; ◙ -U2/U1 = 0.2 ;
□ -U2/U1 = 0.3 ; ▲ -U2/U1 = 0.36

It has been checked that the evolution of U1max/U(x) follows a straight line with the same slope up to the maximum distance from the nozzle (30 diameters) which could be reached with the present instrument carriage.

The turbulent intensity evolution on the jet-axis $\sqrt{\overline{u'^2}}/U(x)$ is in good consistency with the mean velocity result (Fig. 4). A very high level of $\sqrt{\overline{u'^2}}/U(x)$ (up to 40%) is obtained for the case of strongest suction (-U2/U1 = 0.39). In this case, the turbulent intensity first increases rapidly, then relaxes slowly to a level of 28%, which is a little higher than in a standard turbulent jet.

The influence of counterflow on the jet diffusion is summarized on Figure 5, which shows the normalized mean velocity for x/D1=5 as a function of R = -U2/U1max. When this ratio is higher than 0.06 (-U2/U1 ≈ 0.09), the effects of counterflow are very strong. The decrease of U(x/D1=5) is faster than in SW's study. The differences between the two facilities must be again underlined. In particular, the slot width is much smaller in the present experiment, which is likely to give stronger effects of the counterflow.

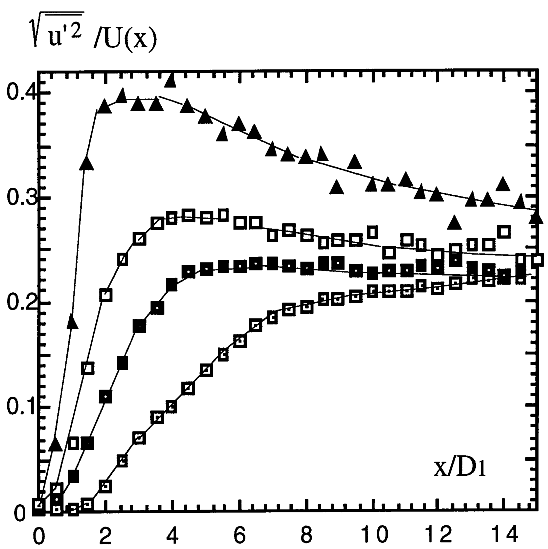

Fig. 4. - Axial turbulence intensity profiles.
same symbols as in Fig. 3

Spectra

SW found spectra with a preferred frequency independent of the distance to the nozzle for conditions of sufficiently strong suction. Referring to the linear theory, they interpreted this global instability as the result of self-excitation in the jet when the conditions of absolute instability ((-U2/U1max)crit = 0.136) are reached in a sufficiently large region of the flow (Strykowski and Niccum 1991, 1992). In the present experiment, no such preferred frequency was observed whatever the conditions of suction. For example, Figure 6 shows the velocity-fluctuation spectra measured at x/D1 = 3 without and with suction.

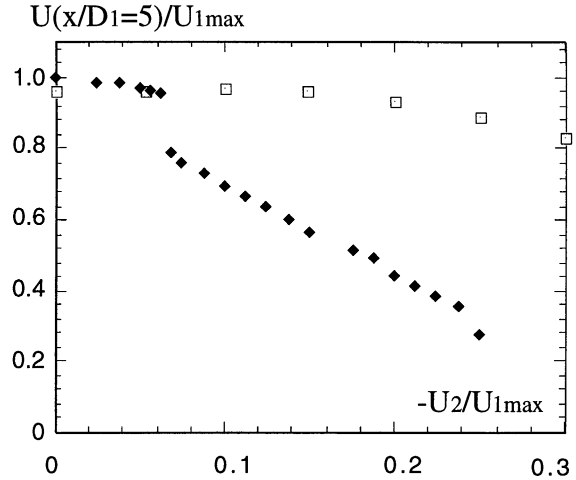

Fig. 5. - Jet axis-velocity at x/D1 =5. Comparison with Strykowski and Wilcoxon's results:
◆ present study, □ SW's results.

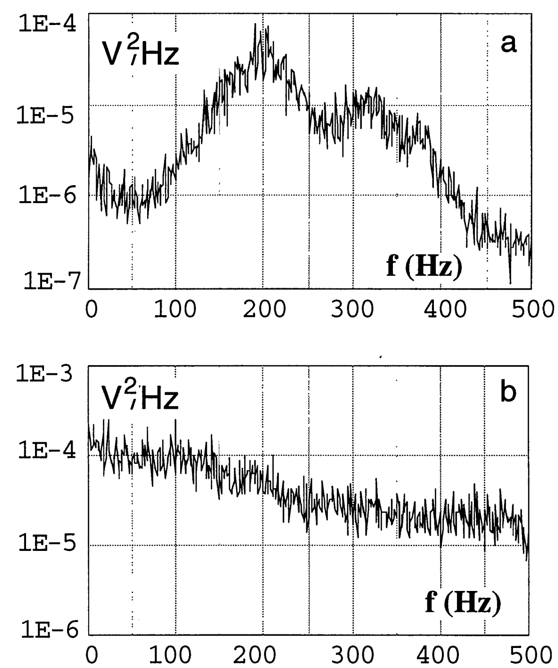

Fig.6.- Velocity-fluctuation spectra. x/D1 = 3
a) without suction ; b) R=0.14

Without counterflow, the Kelvin-Helmholtz preferred frequency clearly appears in the spectrum (Stouhal number S = 0.5). When strong suction is applied, velocity-fluctuations are enhanced in a large low-frequency bandwidth and no preferential frequency is observed.

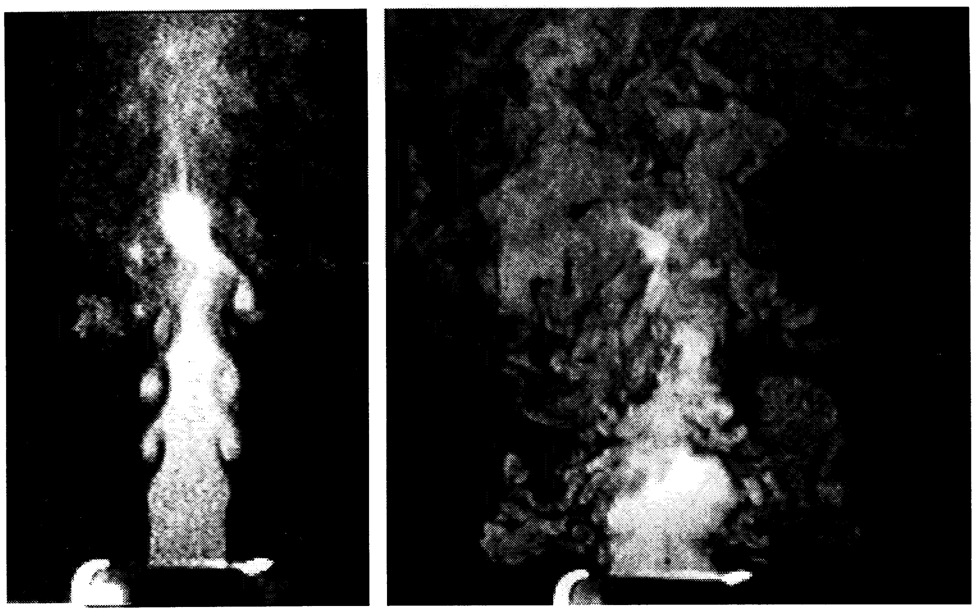

Fig. 7.- Laser-sheet visualizations.
Left : no counterflow, right : -U2/U1 = 0.36

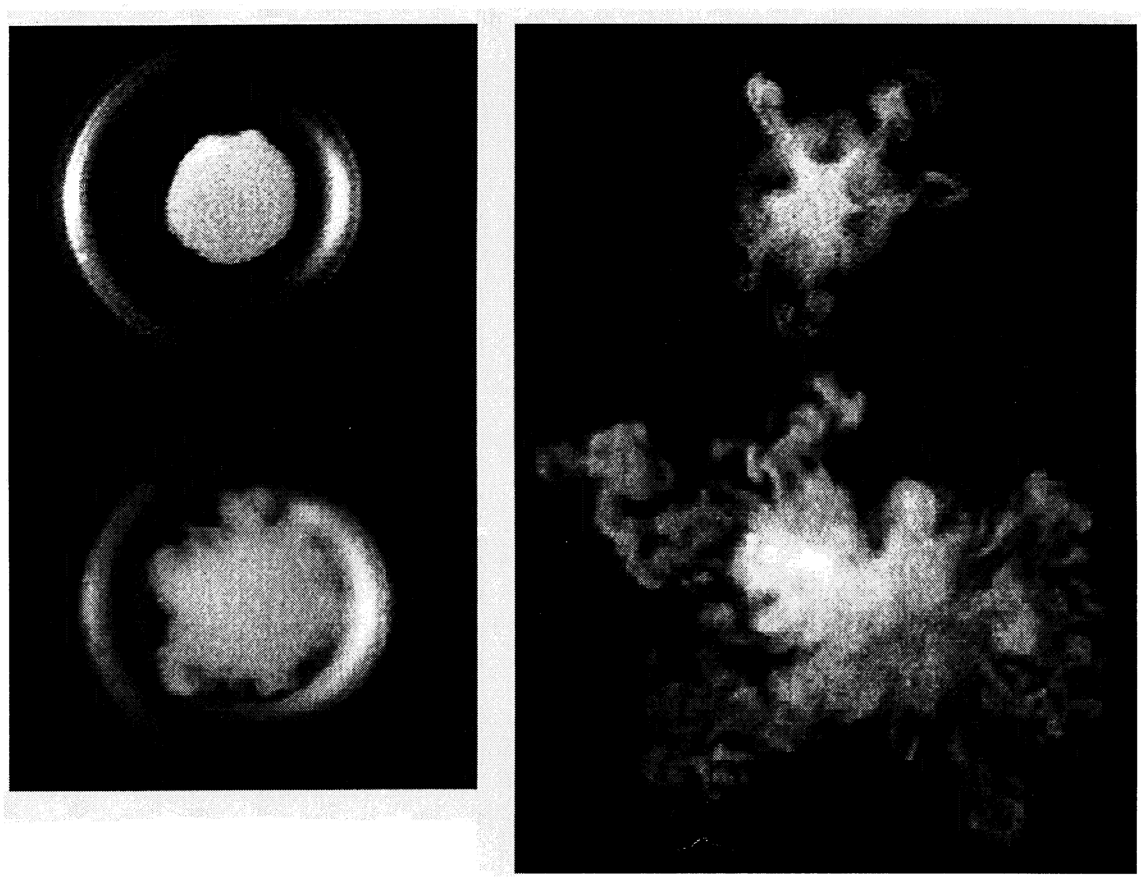

Fig. 8.- Cross-sectional views of the jet
Left : x = 0 ; Right : x/D1 = 3
Top : without counterflow ; Bottom : -U2/U1 = 0.36

Visualizations

The visualizations (Fig.7) confirm the strong influence of the counterflow on the spreading of the jet. Without counterflow, axisymmetrical vortices grow in the jet mixing layer. When strong suction is applied, the jet appears as highly intermittent from the collar exit (visible on the photographs). Very large scale ejections of fluid are observed at some instants in the very first diameters as on the view shown here. Cross-sectional views (Fig.8 bottom) show the very large extent of the jet during ejections.

Visualizations and spectra are in agreement to show that the strong enhancement of diffusion and mixing observed in the first diameters of the present jets with counterflow is not due to a phenomenon of global instability as in SW's experiment.

Flow in the suction collar

When conditions of strong suction are applied, a fraction of the flowrate which issues from the central nozzle is ingested by the suction slot (Fig. 9). In other words, the flowrate in the aspirating slot is composed of q'1, issuing from the central jet and q'2, coming from the ambient air.

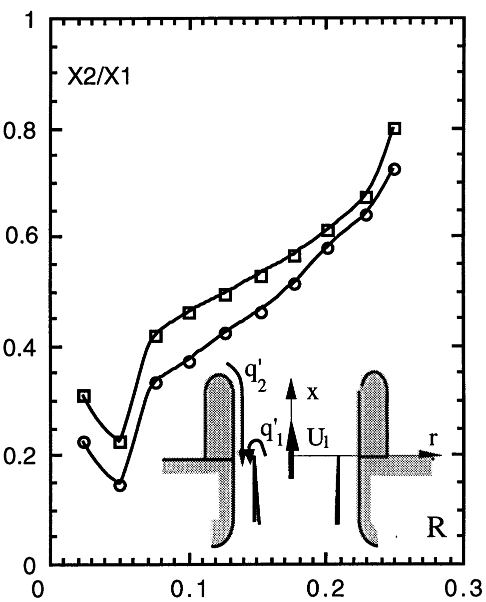

Fig.9.- Ratio of aspirated flow concentration to central jet concentration. R = -U2/U1max.
o , X1 = 0.1 , □ , X1 = 0.2

We denote Y the fraction of q'1, relative to the total aspirated flowrate :

$$Y = q'1 / (q'1 + q'2) \qquad (1)$$

Y was estimated by using a mixture air-helium (molar fraction of helium : 10% and 20%) for the jet flow and by measuring the concentration of the sucked flow.

If we denote respectively X1 and X2, the molar concentrations of helium in the central jet and in the aspirated flow, conservation of helium flowrate yields :

$$X1\, q'1 = X2\, (q'1 + q'2) \qquad (2)$$

and Y is deduced easily from the above equation.

The molar fraction X1 was controlled by a set of sonic throat orifices of different sizes placed upstream of the nozzle. X2 was measured with an aspirating probe similar to that developed by Brown and Rebollo (1972). It consists of a hot-wire placed inside a thin tube and exposed to a flow of the mixture aspired at the measurement point. When the probe is operated at sonic conditions, the hot-wire is only sensitive to density variations. This probe was extensively used by Favre-Marinet et al (1997) to study flows with large density differences. X1 was chosen as low as possible to have negligible density effects on the jet dynamics and to ensure sufficient measurements accuracy. The aspirating probe was placed between the pump and the flow meter, which was used to measure the flow rate, far downstream from the nozzle.

It is observed (Fig. 9) that Y first decreases slightly, then increases rapidly when the suction ratio R = -U2/U1max becomes higher than 0.06. Since the critical value of the suction ratio R is the same for the centerline velocity evolution (Fig.5), this suggests that recirculation may play a significant role to produce low-frequency fluctuations in the cavity.

DISCUSSION AND CONCLUSION

The present flow conditions are likely to correspond to a large positive pressure gradient in the cavity and to a subsequent strong recirculation near the central jet exit. The present results suggest that recirculation in the cavity could destabilize the initial mixing layer and contribute to the high level of turbulence and to a rapid diffusion in the first diameters of the jet.

The differences with SW's results could be due to the different geometrical conditions in the two experiments. In our case, the nozzle is preceded by a rather long tube and the exit velocity profile presents mild radial velocity gradients in the shear layers (Fig.2). In SW's experiment, the converging nozzle is characterized by a "top-hat" profile. This thin shear-layered flow is consequently more unstable than the present one. Moreover, suction effects are stronger with a narrow slot and the present flow is probably far from a parallel shear flow. Unfortunately, investigations of the flow in the collar by visualizations or by hot-wire measurements are very difficult.

Visualizations are uneasy due to the axysimmetrical geometry. Interpretation of the hot-wire signal is dubious because the flow direction is strongly time-varying in the shear layers near the nozzle exit.

A general conclusion is that the counterflow technique is very efficient to control the diffusion and the turbulence level in the near-field of a round jet in a simple way.

ACKNOLEDGEMENTS

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