EXPERIMENTAL AND NUMERICAL INVESTIGATION OF JET CONTROL FOR ACTIVE CONTROL OF COMBUSTION INSTABILITIES

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ABSTRACT

Controlling the mixing of a gas (usually fuel) issuing from a tube into surrounding air is a basic problem in multiple combustion systems. The purpose of the present work is to develop an actuator device to control the mixing enhancement of an axisymmetric non reactive jet. The actuators consist of four small jets feeding the primary jet flow. These four jets are oriented to add an azimutal component to the velocity field. The influence of the deflection between the axis of control and main jets will be discussed. Schlieren photographs will be used to compare the efficiency of the two configurations of interest and hot wire anemometry to quantify the effect of the control to main flow rate ratio.

Large Eddy Simulations (LES) of both forced and unforced configuration are also performed. The objectives of the numerical part of this work are to understand the actuators effect and to validate LES as a tool to study active control.

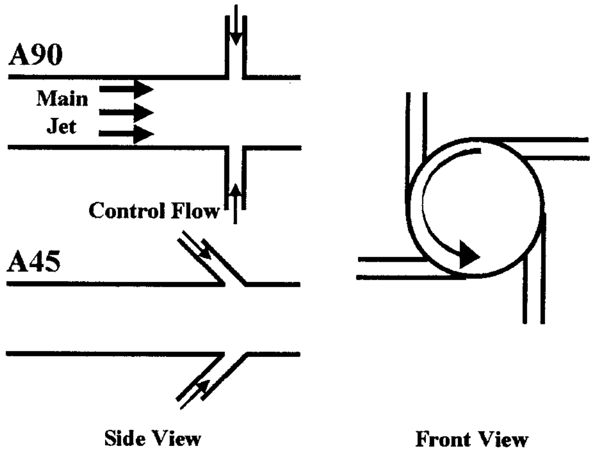

Figure 1: Schemes of the A45 and A90 configurations.

INTRODUCTION

Combustion instabilities may occur in closed combustion chambers, resulting from the coupling between acoustics and combustion. They can appear in many combustors such as gas turbines or industrial furnaces. Those instabilities are responsible for noise, vibrations and sometimes complete device failures (Mc Manus *et al.*, 1993). That is the reason why so many studies focus on the control of combustion instabilities. There are two ways for controlling a flow. Passive control consists in modifying the geometry of the burner (Gutmark et *et al.*, 1999) and/or the combustion chamber ; on the other hand active control consists in injecting external energy through actuators. The quality of the control is then achieved by the design of the actuators. Some of them are specific to combustion applications but most techniques developed for actuation are encountered in both reactive and non reactive applications : loudspeaker, synthetic jets (Davis *et al.*, 1999), flaps (Susuki et *et al.*, 1999).

The purpose of the present study is to quantify experimentally and numerically the effects of forcing on the aerodynamic field in a model configuration : a non reactive jet of air. The actuators are designed to produce two effects :

- radial fluid injection into the main jet, which enhances the mixing of the jet with the ambient air (Delville *et al.*, 2000),
- swirl addition, which changes drastically the aerodynamic pattern of the flow and can be used to stabilize the flame (Beer and Chigier, 1972).

To obtain these effects simultaneously, the actuators of the present work consist of four small jets feeding the primary jet flow. These four jets are oriented to add an azimutal component to the velocity field. To visualize the effect of the actuators on the main flow, both hot-wire anemometry and schlieren photographs are used.

Because LES cost is very high, simulations can not be performed on each actuators configuration that is experimentally tested. The strategy adopted was the following one : first, experiments are used to establish which of the actuators configuration is the most efficient in term of mixing enhancement ; after this choice, LES of this configuration only are performed to understand how the actuator actually affect the main jet.

EXPERIMENTAL FACILITY

Figure 1 shows a scheme of the nozzle equipped with the actuator. The exit diameter of the main jet (D) is 10 mm while the exit diameter of each small secondary jet is 2mm. Previous investigations have shown that the exit diameter of the small jet is one of the numerous parameters which have an influence on the control efficiency (Faivre and Poinsot, 2002). Here, an other parameter will be tested : the orientation of the four small jets compared to the main one. To evaluate the importance of this parameter, two configurations of actuators are tested :

- A90 : The four small jets are in the same plane, which is orthogonal to the direction of the main jet.
- A45 : The four jets are deflected of 45°.

For both configurations, the control jets are tangential to the main one to add an azimutal component to the velocity

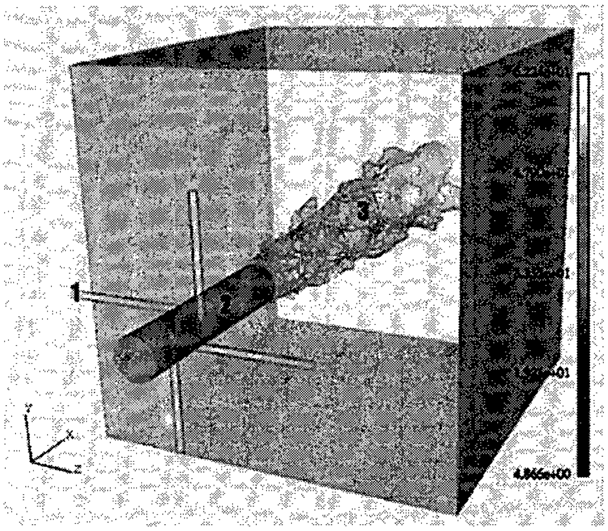

Figure 2: Computational domain. 1 : actuators. 2 : main flow. 3 : jet blowing in the box.

field. The control flow is injected three main jet diameters upstream of the nozzle exit.

The nozzle is connected to a cubic box so that the jet flow is confined. The characteristic length of the box is 10 diameters of the main jet.

The main air flow is delivered thanks to an hot air generator. This device allows to reach mass flow rates up to 30 g/s at 400°C. The air generator is coupled to a mass flowmeter to avoid any main flow rate decrease due to the additional head loss that appears when controlling the flow. The secondary flow (the control flow), is driven from another air compressor to the nozzle. The control flow rate is measured by a DANTEC S2140 Mass Flow Transducer, which has been specially modified for the present work to measure unsteady flow rates up to 1 g/s at a frequency up to 500Hz. The ratio between the mass flow rate of the main jet and the mass flow rate of the control flow is :

$$q = \frac{\dot{m}_{act}}{\dot{m}_{jet}} \quad (1)$$

where $\dot{m}_{act}$ is the control mass flow rate and $\dot{m}_{jet}$ the main mass flow rate. It is adjusted with a servovalve MOOG. This servovalve works both in continuous and pulsated regime. Its most interesting particularity is that it can reach a high frequency (400 Hz) while typical servovalves do not exceed 25 Hz. The jet spreading is characterized by the mean and rms velocity fields measured with a single hot-wire probe. The flow is also visualized through schlieren photographs to measure its spreading angle.

NUMERICAL SETUP

The principle of LES is to resolve the larger scales of turbulence while modelling the smaller ones. LES should be a good tool to predict the effect of the control on the flow because large structures are certainly the most involved.

LES of the experimental configuration are performed using the parallel CFD code "AVBP" developed at CERFACS in Toulouse, France and at IFP in Paris, France. AVBP solves the full compressible Navier-Stokes equations on 2D or 3D meshes. Meshes can be structured, unstructured or hybrid. All the simulations that will be discussed here are three dimensional and based on a hybrid mesh (1 million points for 700.000 cells). Figure 2 shows the computational domain. Note that, even for the unforced case, the actuators are included in the mesh.

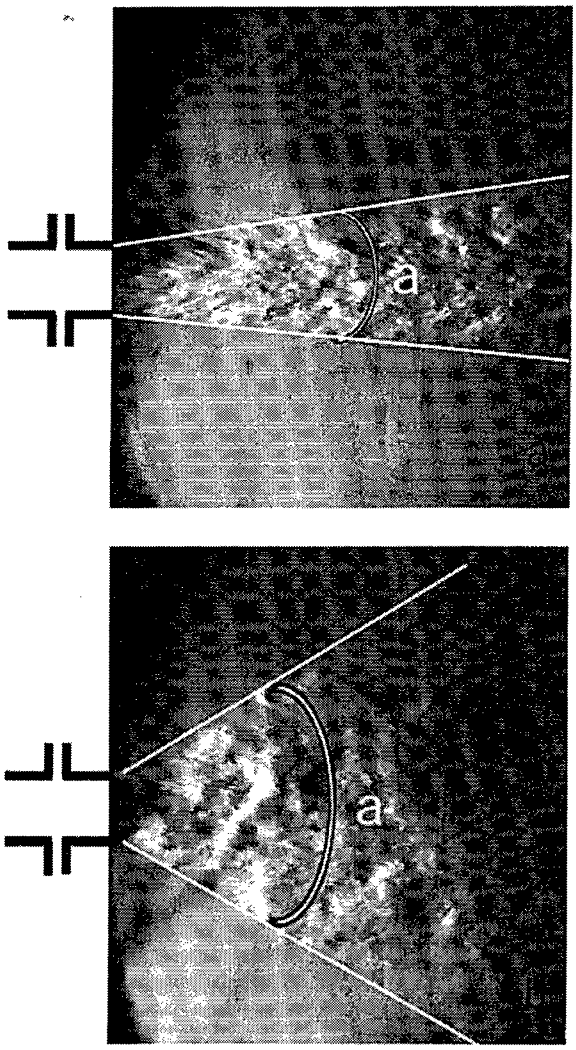

Figure 3: Schlieren photographs of the unforced flow (a) and the forced one (b). Evaluation of the jet spreading angle.

RESULTS

Experimental results

The first step is to evaluate which of the A45 or A90 is the most efficient. To quantify the effect of a configuration, a criterion based on the jet spreading angle is used. The measure of this angle is based on strioscopic photographs like those on figure 3. As shown on figure 3, the estimation of the jet spreading angle is done including the large structures of the shear layer.

Different control to main mass flow rate ratios (q) have been investigated and figure 4 shows the evolution of the jet spreading angle when increasing q. It appears clearly that the mixing is enhanced when controlling the flow with one of the actuators. However, it seems that the A90 configuration is the most efficient. In fact, except for very low values of q, the jet controlled by the A90 actuator is larger than the one controlled by the A45 actuator at the same control mass flow rate. The orientation of the four small jets has therefore

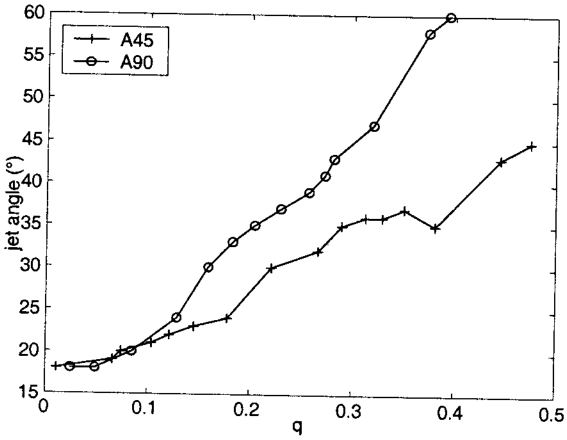

Figure 4: Jet spreading angle vs. control to main mass flow rate (q) for A45 and A90 configurations.

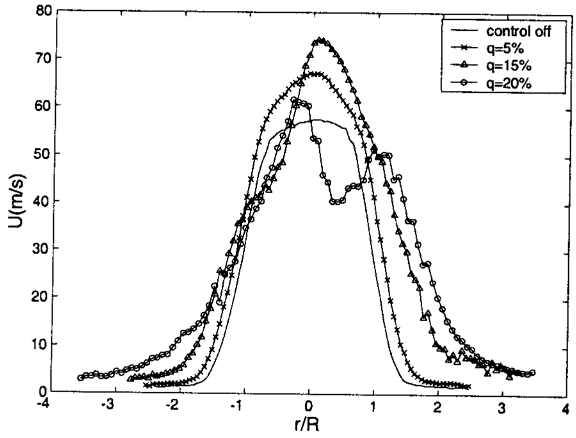

Figure 5: Radial profiles of mean axial velocity at x/D = 5 for different control flow rate. Experimental results.

an effect on the efficiency of the control.

One possible explanation is that, at equal control flow rate, the azimutal component added to the velocity field is larger for the A90 than for the A45 configuration : the four small jets wind more easily round the main jet in the A90 configuration. The A90 actuator only adds an azimutal component to the velocity field while the A45 actuator adds both azimutal and axial components and therefore the main flow sweeps the actuators effect along the jet axis more easily.

As the A90 configuration has been identified to be more efficient that the A45, it was retained for all further studies.

Figure 5 shows the effect of the increase of the control to main mass flow rate ratio on the mean radial profiles of axial velocity at x/D=5, where D is the main jet exit diameter. At low control mass flow rate, the mixing with the ambient air is a little enhanced, but not very significantly. When increasing the control flow rate, the mixing with the ambient air is enhanced. For q equal to 0.2, the jet width is close to twice the width of the unforced jet. The jet centerline velocity is affected by the control too. In fact, for low values of q, the jet centerline velocity increases with q. But, for q high enough (here q=0.2) this trend changes and a velocity centerline deficit appears. The profile for q=0.2 is very close to one which is expected for a swirled flow at low swirl number. Figure 6 shows the effect of the increase of the control to main mass flow rate ratio on the mean radial profiles of rms axial velocity at the same position. The influence of the control to main mass flow rate ratio appears clearly : the higher is the control flow rate the larger is the urms profile. It confirms that the mixing with the ambient air is enhanced by the control : the mixing zone width increases with q. It has to be noticed that the amplitudes of the velocity fluctuations increase with q too. For q=0.2, the shape of the rms velocity profile is completely different from the other cases. It may be the signature of a central recirculation zone whose position fluctuates with time.

These experimental results are sufficient to determine which of the A45 or A90 is the most efficient : the A90 actuator enhances the mixing of the jet with the ambient air in a significant way. Velocity profiles show that the entrainment of the ambient air is favoured when increasing the control to main flow rate ratio. Many profiles have been stored so that it constitutes a database for the comparison with the numerical results.

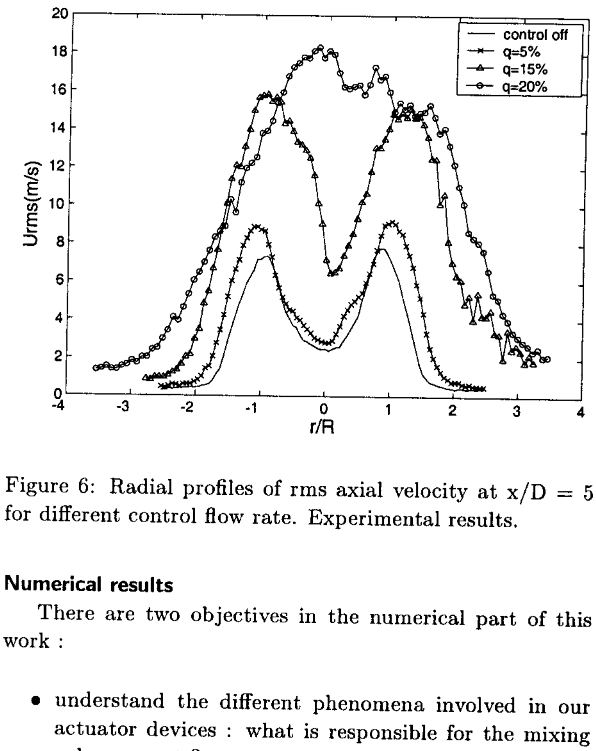

Figure 6: Radial profiles of rms axial velocity at x/D = 5 for different control flow rate. Experimental results.

Numerical results

There are two objectives in the numerical part of this work :

- understand the different phenomena involved in our actuator devices : what is responsible for the mixing enhancement ?
- validate LES as a tool to study active control : is there a good agreement between experimental and numerical results ?

LES is validated first on the unforced case. Figure 7 to 9 show radial profiles of mean and rms axial velocity at different distances from the jet nozzle exit (resp. xD= 1, 4 and 6), for both numerical and experimental tests. The mean profiles are in good agreement, except close to the shear layer zone. This is probably due to two things : first, as there is no wall law in the LES, it is difficult to predict the effect of friction which affects the velocity profile and second the hot wire can not distinguish if the local velocity is positive or negative. This difference occurs only inside the potential core. In fact, in the LES, the potential core is directly affected by the velocity profile imposed at the inlet of the computational domain. That explains why figure 7 and 8 clearly show that the centerline velocity is overestimated in

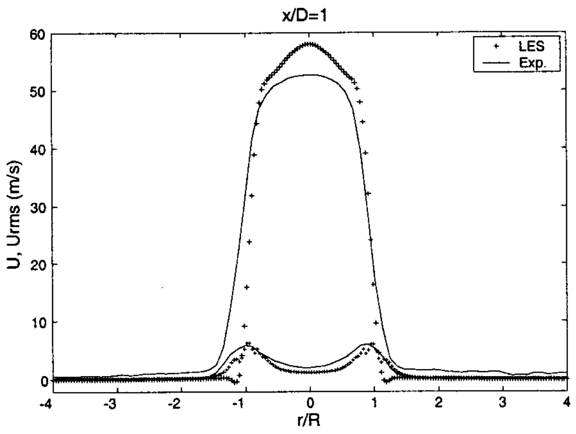

Figure 7: Radial profiles of mean and rms axial velocity at x/D=1. Comparison between experimental and numerical results for the unforced case.

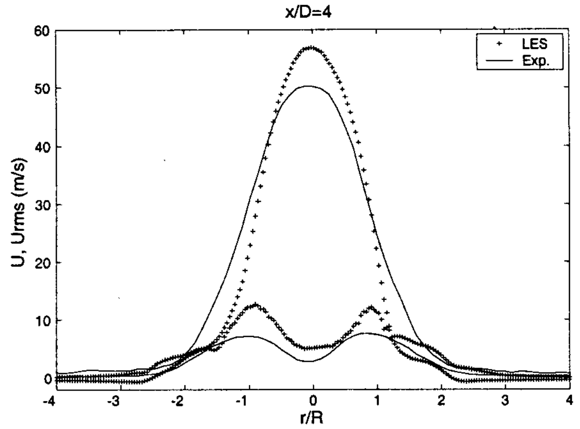

Figure 8: Radial profiles of mean and rms axial velocity at x/D=4. Comparison between experimental and numerical results for the unforced case.

the LES. At x/D=6, figure 9 shows that, outside the potential core, the LES and the experiments are in very good agreement. Globally, the jet spreading angle is well evaluated. The mean rms axial velocity profiles show that LES overestimates the fluctuation of axial velocity, especially in the potential core region.

LES of the forced case have been performed too. Figure 10-a, b, c and d show the flow field of a numerical tracer injected only through the actuator. This tracer has been normalized to obtain the function z which is equal to 1 if the species injected through the actuator is present and 0 if not. Figure 10 represents cross sections of the flow inside the nozzle at different distances from the control flow injection zone. Figure 10-d shows the boundary surface of the nozzle. The cross sections at a distance of 0.5 and 1.5 cm from the control flow injection (figures 10-a and 10-b) reveal that the four small jets wind round the main jet while penetrating inside it. This rotating movement does not continue downstream of the actuators as shown in figures 10-b and 10-c. It seems that after having winded round the jet, the energy provided by the actuator is not strong enough to put the main jet in rotation. To complete this information on the flow structure, figure 11 presents the mean axial velocity field on the cross section at a distance of 2,5 cm from

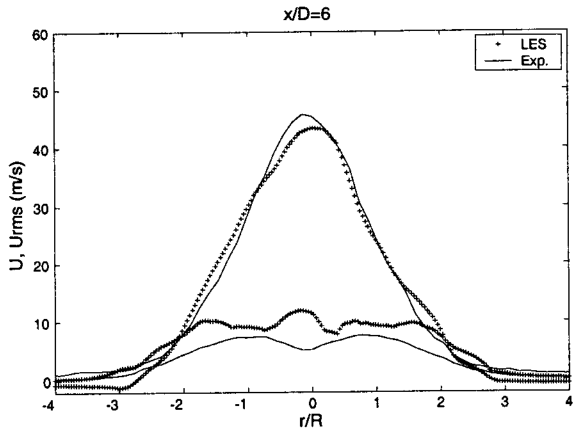

Figure 9: Radial profiles of mean and rms axial velocity at x/D=6. Comparison between experimental and numerical results for the unforced case.

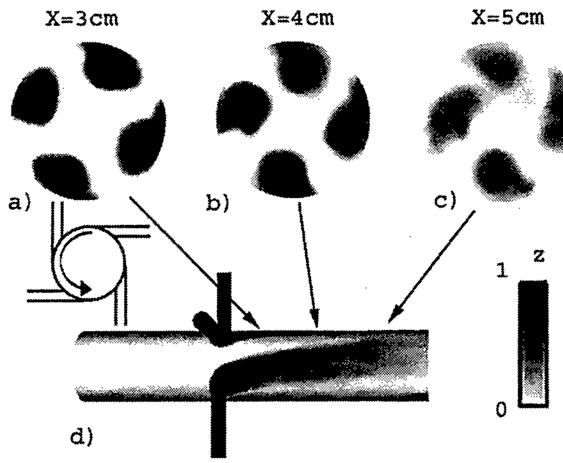

Figure 10: Actuators effect on the flow inside the nozzle. Fields colored by a tracer injected through the actuator. Cross sections at different distances from the control flow injection area (a,b,c). Boundary surface of the nozzle (d).

the control flow injection. Two dimensional vectors have been superposed to the field : each of those is the projection of the local three dimensional velocity vector on the plane of interest. This allows to notice that the four jets rotate around their own axis and induce locally a decrease of the mean axial velocity. The jets act as obstacle for the main flow increasing the pressure loss in this region for the main jet. Figure 11 shows that the external layer of the flow inside the nozzle has been put in rotation by the control flow.

The next step is to study the jet spreading after the jet nozzle exit. To explain that, the velocity has been computed in a cylindrical coordinate system. Figure 12 shows the orthoradial velocity (u_θ) field at a distance of x/D=1 from the jet nozzle exit for both forced and unforced configuration. The level of u_θ reached in the forced configuration is very high compared to the one of the unforced case. One has to notice that the scales are different in both cases. It shows that the control device has the expected effect : it adds swirl to the flow. This swirl is responsible for the mixing enhancement with the ambient air as shown on figure 13 which displays the radial velocity component (u_r). Its meaning is simple : if $u_r > 0$, then the flow locally moves away from the centerline and if $u_r < 0$, the flow locally moves closer to the centerline. In other words, figure 13 shows that the entrainment of the ambient air by the jet is very significantly enhanced when controlling the flow. Figure 14 shows mean velocity profiles at different distances from the jet nozzle exit. LES also confirms the fact that mixing is enhanced : the profile width increases considerably and the centerline velocity decreases as the distance to the nozzle exit increases when the control is actuated. Comparison with experiments are still underway and will be presented at the conference.

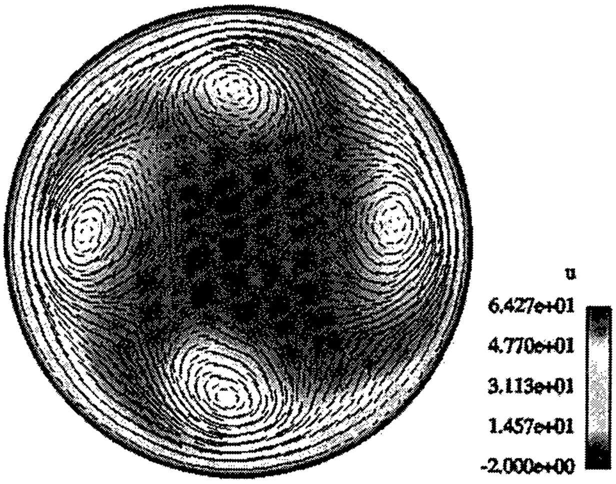

Figure 11: Actuators effect on the flow inside the nozzle : mean axial velocity field and 2D velocity vectors at 2,5 cm from the control flow injection.

CONCLUSION

Experimental and numerical investigations of the control of a jet by four radial actuation jets has shown that swirl injection (obtained by shifting the axis of actuators jets) is an efficient way to control mixing and jet spreading. The importance of the deflection between the control jets axis and the main one has been established. The most efficient configuration in term of mixing and jet spreading enhancement is the A90 actuators device. Large Eddy Simulations have been validated on the unforced case. The simulations of the flow controlled by the A90 actuator reveal which mechanisms are responsible for the control efficiency : the control jets add swirl (which was expected from the design of the actuators) that enhances the jet spreading. However, the LES reveals that the actuators choice (4 small jets) induces also secondary vortices which may play a role for the reacting cases.

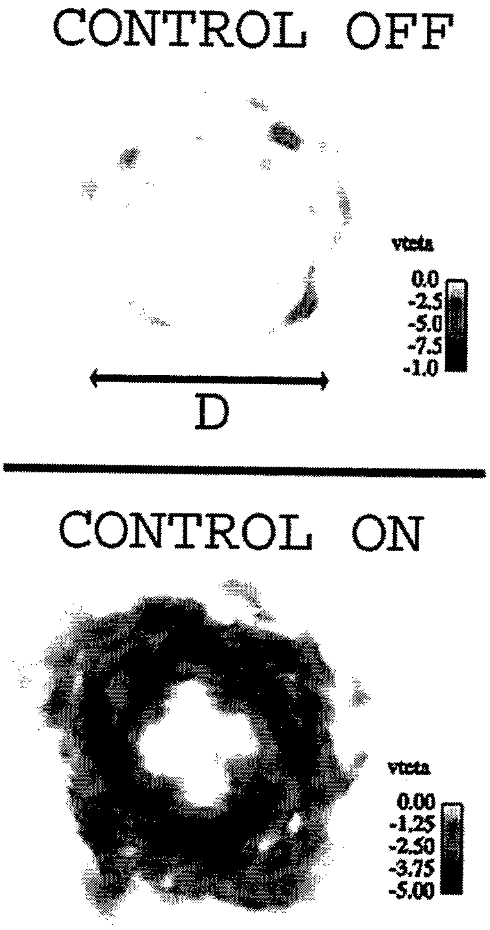

Figure 12: Flow field of orthoradial velocity component at x/D=1 for both forced and unforced cases.

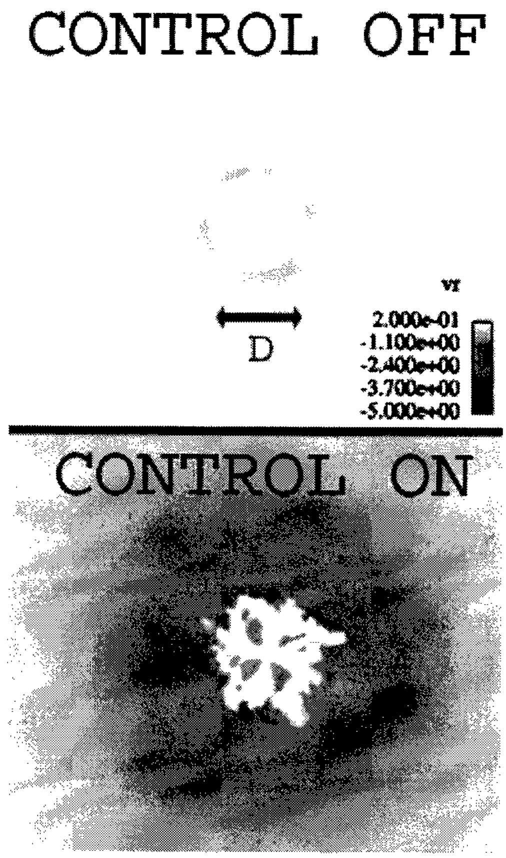

Figure 13: Flow field of radial velocity component at x/D=1 for both forced and unforced cases.

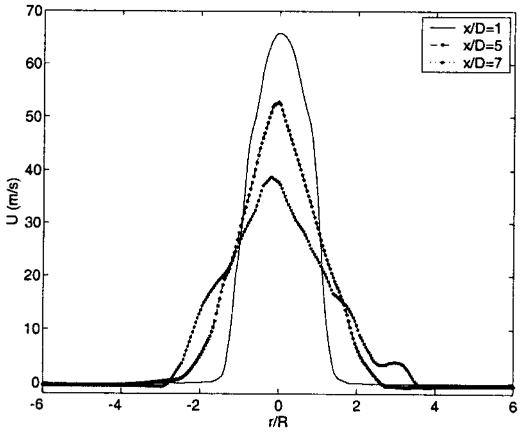

Figure 14: Mean axial velocity profiles in the forced case (q=0.15) at different distances from the nozzle exit. Numerical results.

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