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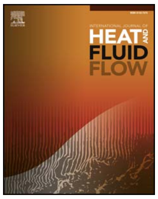

Numerical investigation of plasma-controlled turbulent jets for mixing enhancement

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ABSTRACT

Plasma-controlled turbulent jets are investigated by means of Implicit Large–Eddy Simulations at a Reynolds number equal to 460,000 (based on the diameter of the jet and the centreline velocity at the nozzle exit). Eight Dielectric Barrier Discharge (DBD) plasma actuators located just before the nozzle exit are used as an active control device with the aim to enhance the mixing of the jet. Four control configurations are presented in this numerical study as well as a reference case with no control and a tripping case where a random forcing is used to destabilize the nozzle boundary layer. Visualisations of the different cases and time-averaged statistics for the different controlled cases are showing strong modifications of the vortex structures downstream of the nozzle exit, with a substantial reduction of the potential core, an increase of the jet radial expansion and an improvement of the mixing properties of the flow.

1. Introduction

Turbulent jets are used in a variety of industrial applications, such as jet engines and combustion chambers. Greenhouse gases, toxic pollutants, heat ejection and sound radiation emitted from such devices are often detrimental to the environment. Enhancing specific properties of a jet is therefore vital. For instance, improving its mixing property would result in higher thrust for a jet engine and more energy extraction due to a more complete combustion in the combustion chamber. A comprehensive review of research activities for the control of turbulent jets in the last 50 years can be found in Zaman et al. (2011).

Strategies in order to enhance the performance of turbulent jets fall in two control categories, passive and active. Passive control usually involves geometric modifications of the nozzle by using notched nozzles (Pannu and Johannesen, 1976), tabs (Bradbury and Khadem, 1975; Ahuja and Brown, 1989; Samimy et al., 1993) and chevrons (Brausch et al., 2002; Callender et al., 2005; 2008). Even though no external energy is added to the flow, these devices are always present which could result in performance penalties. For example, in the case of an airplane during cruise, a jet engine with chevron nozzles can experience thrust penalty (Zaman et al., 2011; Calkins and Butler, 2004). At first, control studies were directed into varying the geometry of the nozzle, i.e. elliptic (Husain and Hussain, 1983; Hussain and Husain, 1989; Ho and Gutmark, 1987), or rectangular nozzles (Gutmark et al., 1989; Quinn, 1991). Experiments were performed in Ho and Gutmark (1987) using a small-aspect-ratio elliptic nozzle to demonstrate that the entrainment ratio can be greatly enhanced by comparison to a circular or a planar jet. The flow was seen to experience axis switching: the major and the minor axes of the elliptic cross-section of the jet were alternating along the downstream direction resulting in a larger engulfment of the surrounding fluid into the jet. Hot-wire anemometry experiments were performed in Quinn (1991) with rectangular nozzles of aspect ratio 2 and 10. The authors observed an increase in the near field mixing due to higher shear-layer values of the turbulent kinetic energy and the Reynolds stress, as well as a shorter potential core length for a nozzle with aspect ratio 10.

Boeing, General Electric, and NASA have developed serrated edges called chevrons for the back of the nacelle and the engine exhaust nozzle and they found that chevrons can reduce jet noise up to 4 dB, however associated with a reduction of thrust and a loss of 0.25% on fuel consumption (Saiyed et al., 2000; Nesbitt et al., 2002; Bridges and Brown, 2004). Experiments with a coaxial flow test rig were carried out in Callender et al. (2005, 2008) to study different chevron nozzles over a wide range of operating conditions. The numbers of lobes and levels of penetration were varied in order to evaluate the impact of these geometric parameters on the noise level. All configurations achieved a reduction of 3–6 dB for the overall Sound Pressure Level (SPL). Calculations of perceived noise level directivity also showed a 4–6 dB reduction at aft angles. It was also observed that the chevron penetration was the primary factor to control the tradeoff between low-frequency reduction and high-frequency SPL increase and to influence the size and intensity of the noise region near the nozzle lip. Hybrid Reynolds-

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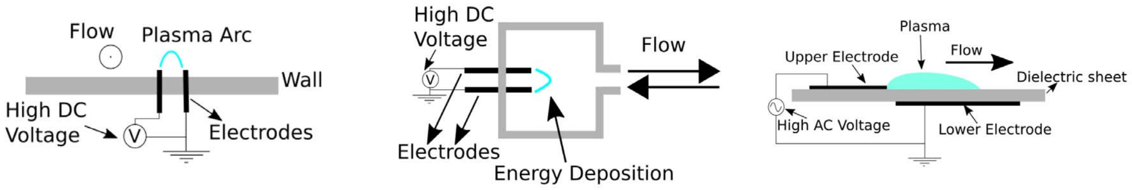

(a) LAFPA (b) PSJ plasma actuator (c) DBD plasma actuator

Fig. 1. Simplified schematics for LAFPA, PSJ and DBD plasma actuators.

averaged Navier–Stokes (RANS) - Large–Eddy Simulations (LES) of chevron jet flows were performed in Xia et al. (2009) in order to generate noise predictions. It was found that for a Mach number equal to 0.9, the numerical data compare favorably with measurements for the flow field, with encouraging agreement of the predicted far field sound directivity and spectra obtained using the Ffowcs Williams and Hawkings (FWH) surface integral method. The main conclusion was that the chevron penetration angle is a critical parameter to achieve noise mitigation.

To avoid the disadvantages of passive modifications, most of the research related to turbulent jets is nowadays focusing on active control solutions for which energy is only added to the flow when needed. In a similar way to passive control solutions, they are designed to manipulate the topology of the flow, either by provoking instabilities or by directly targeting the destruction or creation of large-scale structures. Various strategies have been studied for active control, such as synthetic or piezoelectric jet actuators (Butler and Calkins, 2003; Low et al., 2010; Önder and Meyers, 2014), secondary jets (Lardeau et al., 2002; Maury et al., 2009; 2011; Gautier et al., 2014) and plasma actuators (Samimy et al., 2004; 2007a; 2007b; Kim et al., 2009; Gaitonde and Samimy, 2010; 2011).

Piezoelectric actuators for turbulent jet control were assessed in Butler and Calkins (2003) to investigate if they could alter the turbulent energy distribution. These actuators produced small-scale disturbances in the shear layer just at the nozzle exit. Particle Image Velocimetry (PIV) snapshots showed an increase in vorticity in the near field while an array of microphones showed a shift of the peak values for low emission angles. This shift was attributed to the fact that the large coherent structures were annihilated, in conjunction with a good anisotropy for the small scales. A different approach was taken in Low et al. (2010) where pressure readings downstream of the nozzle were used to conduct open and closed loop control tests using synthetic zero net-mass-flux (ZNMF) actuators radially placed at the nozzle exit. The authors managed to show the ability of their control technique to modify the near field region flow features but with very little impact of the far field noise spectra. The near field of a ZNMF actuated round jet using Direct Numerical Simulations (DNS) was studied in Önder and Meyers (2014) for a low Reynolds number of 2,000 (based on the diameter of the jet and the centreline velocity at the nozzle exit). Strong deformations of the near-field jet region were observed which were very similar to those observed for non-circular jets. These changes were attributed to the self-deformation of the jet's primary vortex rings due to distortions in their azimuthal curvature and by the production of side jets by the development and subsequent detachment of secondary streamwise vortex pairs.

Secondary jets with a mass flow rate of 10% of the main jet at an angle of 45° were used in Lardeau et al. (2002) with DNS of a turbulent jet at low Reynolds numbers equal to few thousands. A reduction of the potential core length associated with a significant jet expansion were observed and, surprisingly, the injections of fluid by the secondary jets did not result in a big enstrophy increase for the main jet. The mixing of the flow was shown to increase, especially when the secondary jets were pulsating. Steady and unsteady fluidic actuators, in the form of secondary control jets injecting from the nozzle lip were investigated experimentally in Maury et al. (2009, 2011). The actuation comprised an azimuthal distribution of 16 nozzle-lip mounted microjets, injecting fluid at a penetration angle of 60°. Different geometrical configurations were explored by varying the distance between the microjets and in particular microjets that converge in pair. The authors concluded that steady and unsteady forcing affect differently low order statistical moments of the velocity field and that the response of the flow to unsteady forcing appears to comprise a non-linear component, at the main forcing frequency, and two secondary components that compare well with predictions of linear stability theory. Up to 2.4 dB of global sound reduction was reported in these experiments. The same number of microjets in a converging configuration, called fluidevrons, was used by Gautier et al. (2014) to perform DNS for a jet at a low Reynolds number equal to 10,000. It was shown that the secondary jets can destroy the large annular structures generated at the exit of the nozzle, accelerating the generation of smaller scales in the near field, resulting in an increased turbulent kinetic energy. A distinct flow pattern was observed with some ejections from the main jet into the surrounding fluid, and horseshoe vortices generated by the microjets in the near field. As a result, the potential core was observed to increase in length.

Another form of active control for turbulent jet is based on plasma actuators, which are small devices that use high electric potential to accelerate portion of the flow field. Three main types have already been used for turbulent jets, Localised Arc-Filament Plasma Actuators (LAFPA), Plasma Synthetic Jet (PSJ) actuators and more conventional Dielectric Barrier Discharge (DBD) plasma actuators, as seen in Fig. 1. A LAFPA consists of two pin electrodes side-by-side on the wall and when an electric potential difference is applied between them an arc-filament plasma is created. A high temperature, high pressure perturbation is formed, which acts in a similar way to a tab (Samimy et al., 2004). This perturbation can destabilise the boundary layer inside the nozzle, resulting in vorticity generation and triggering of instabilities (Utkin et al., 2006; Samimy et al., 2007b). A PSJ actuator is a zero-net-mass-flux device mainly composed of two electrodes embedded in a cavity in connection with the external medium, with the help of a small dedicated orifice. By applying a voltage difference, an electrical arc is created between the two electrodes, leading to an increase in the internal energy. Since the air is confined, the temperature and pressure increase very quickly inside the cavity, producing a pulsed air jet (Caruana et al., 2013; Laurendeau et al., 2015). DBD actuators are based on a high electric potential difference between two electrodes separated by a dielectric material (Moreau, 2007; Corke et al., 2010; Thomas et al., 2009). The first electrode is positioned above the wall of the nozzle and exposed to the fluid flow, while the other is embedded inside the wall. When the electric potential is applied, the air flow is ionised above the exposed electrode and then accelerated along the embedded electrode, while it is also drawn nearer the wall, creating a wall jet effect (Moreau, 2007; Corke et al., 2010; Thomas et al., 2009).

LAFPAs were studied extensively by Samimy's group in the US as an active control solution for turbulent jets at high-Reynolds numbers for high-subsonic and supersonic regimes. Only LAFPAs can provide excitation signals of high amplitude and high frequency for high-speed and high-Reynolds-number flow control. The control strategy is based on the excitation of various instabilities and azimuthal modes of the jet.