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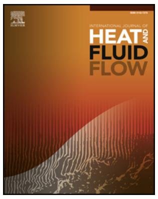

Parametric study of multi-armed jets[☆]

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ABSTRACT

The paper presents the results of numerical simulations of excited incompressible jets with the transport of a passive scalar field. A forcing is obtained through an axial and helical velocity disturbance defined as sinusoidal waves changing in time and travelling in azimuthal direction along the jet border. It includes three control parameters, which determine its strength and temporal behaviour, an amplitude and two characteristic frequencies. The research is performed with the use of direct numerical simulations (DNS) and high-order numerical code based on the compact difference approximation and projection method for the pressure-velocity coupling. The obtained results show that when the axial and helical forcing terms are applied separately, their impact on the flow and passive scalar field is very limited and only quantitative. The situation changes drastically when both forcing terms are applied together. It is found that by a proper choice of the ratio of their frequencies, various type of multi-armed jets can be created, e.g., with 5, 8, or 13 branches. It is observed that the angle at which the branches disjoin from the main jet and an axial location where this phenomenon starts are related to the axial forcing frequency and also to the Reynolds number, to some extent. It is shown that the mixing efficiency analyzed through an evolution of the scalar field or entrainment can be controlled in a smooth way and in a relatively wide range.

1. Introduction

Interest in flow control techniques is driven by a possible improvement of performance, safety and efficiency of various technical devices. Existing strategies of steering and controlling fluid flows can be divided into two approaches: passive and active. The former is based on shaping the flow domains and is usually optimised for specific flow conditions. The latter requires external energy input, which can be varying in response to the instantaneous flow behaviour. The active methods are thus more costly but also much more flexible. Under a variety of different flow regimes, they result in a better overall response than the passive methods. This work concentrates on an active control of a jet flow and focus on fundamental aspects of its dynamics. Despite this rather academic approach, the performed research is valuable also for engineers as the analyzed configuration has many practical applications (burners, rocket nozzle, injectors etc.).

The research devoted to active jet control was initiated in the 70s by a study of Crow and Champagne (1971). It was shown that, with a properly chosen forcing (excitation), a jet changes its qualitative behaviour compared to the natural unexcited jet. It was observed that turbulence intensity and mixing was significantly increased. Direct applications of such active control methods can be found in combustion science where they have been the focus of research since the early 90s (McManus et al., 1993; Annaswamy and Ghoniem, 1995). Frequently, the active control is combined with passive techniques, e.g., in combustion chambers where swirlers act as passive control elements and active control is obtained by an acoustic excitation. By a carefully chosen frequency, the acoustic forcing influences large flow structures that drive combustion instabilities (Hardalupas and Selbach, 2002; Balachandran et al., 2005; Boushaki et al., 2009). This type of excitation is usually obtained by loudspeakers mounted upstream of the nozzle exits (Chao et al., 2002; Abdurakipov et al., 2013). Chao et al. (2002) analyzed the stability of lifted propane-air premixed flames and demonstrated that excitation significantly changes the flame dynamics and may suppress or amplify the stabilization process. The former case happens when the excitation destroys the coherent structures, while the latter when it enhances the vortical entrainment. Demare and Baillot (2004) and Baillot and Demare (2007) analyzed a response of a lifted non-premixed methane flame to acoustic excitation in hysteresis regimes, i.e., when for the same mean flow conditions but different initial conditions, the flame could be attached to a nozzle or remain lifted. It was observed that the attached flames became lifted

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when the excitation led to instantaneous velocities larger than the maximum velocity of the hysteresis regimes.

In case of more fundamental studies on excited jet flows, spectacular examples occurring for a particular forcing method are bifurcating and blooming jets discovered in early 80s. The former are characterized by the occurrence of two well defined, separate branches with vortex rings travelling along the branches, and the latter by a chaotic motion of the vortices (Parekh et al., 1988; Reynolds et al., 2003). The excitation that causes bifurcation or blooming phenomena is introduced at the nozzle exits as a combination of axial and flapping (and helical) excitation. The latter is obtained by a mechanical forcing, which requires the application of sophisticated mechanisms at the nozzle exits (magnetic or piezoelectric actuators). Compared to the acoustic forcing introduced upstream by the loudspeaker, the actuators allow exciting the jet locally (e.g. in the shear-layer only), which is an advantage. Moreover, such an excitation can have characteristics that would not be possible to be achieved with the acoustic forcing methods, e.g., a helical/azimuthal perturbation.

The excited and bifurcating jets have attracted a lot of attention over the last 20 years, particularly in the numerical simulations performed with direct numerical simulation (DNS) (Freund and Moin, 2000; Danaila and Boersma, 2000; Hilgers and Boersma, 2001; Gohil et al., 2010, 2015a) and large eddy simulation (LES) (Silva and Métais, 2002; Tyliszczak et al., 2007; Tyliszczak and Geurts, 2014, 2015). It was confirmed that with properly chosen frequencies of axial (f_a) and flapping (f_f) excitation, the jets bifurcate, and that the strength, localisation and bifurcation angle are directly dependent on the axial forcing and the phase shift between the forcing terms (Tyliszczak and Geurts, 2014). The bifurcation appears when $f_a/f_f = 2$ and it is most pronounced when f_a is close to the so-called preferred mode frequency, i.e., the frequency at which an axisymmetric initial disturbance attains the maximum growth (Burattini et al., 2004; Sadeghi and Pollard, 2012; Ball et al., 2012; Kaushik et al., 2015). Recently, in Tyliszczak (2015a) it was presented that the bifurcation phenomenon can also be created in a diffusion flame and controlled by alteration of the forcing frequency.

A recent work by Tyliszczak (2015b) showed that, apart from the above mentioned bifurcating or blooming jets, different types of multi-armed jets are likely to occur. They reveal as the jets with distinct branches (e.g. 5 or 12) disjoining from the main jet stream a few diameters downstream a nozzle exit. These findings have been later confirmed by Gohil et al. (2015b) who demonstrated that, with particular excitation settings, the jet can split into even 20 distinct branches. Similarly, as the blooming jets, the multi-armed ones are obtained through axial and helical excitations superimposed on an inlet velocity profile, yet with specific ratios of axial to helical (f_h) frequencies. The DNS studies of the multi-armed jets performed in this paper focus mainly on the influence of f_a/f_h and f_a on the characteristics of their splitting. It is shown that, with a particular setting of f_a/f_h, the multi-armed jets can be created, e.g. with 5, 7, 11, or 13 branches, consistently with analytical considerations. It is found that with f_a/f_h kept constant and varying f_a, one may alter a strength of the splitting phenomenon, its spatial location and angle at which the branches disjoin from the main jet. To assess the application of the combined axial and helical excitations for mixing improvement (e.g. for combustion purposes), the applied forcing is analyzed from the point of view of possible influence on the flow entrainment process and the passive scalar field.

2. Solution algorithm

The research is performed for incompressible flow with a constant density and constant temperature but taking into account the transport of the scalar field. The analyzed test characterises relatively low Reynolds number ($\mathrm{Re} \leq 5 \times 10^3$) that allows applying DNS method. The solver is an in-house high-order code called SAILOR, which is based on the projection method for pressure-velocity coupling. The time integration is performed with the application of the Adams–Bashforth / Adams–oulton predictor-corrector method and the spatial discretization is based on the 10th/6th order compact difference method for the velocity field and 5th order WENO (Weighted Essentially Non-Oscillatory) scheme (Shu, 2003) for the convective terms in the scalar transport equation. The discretisation is performed on half-staggered meshes (Tyliszczak, 2014, 2016), where the velocity components and scalar variables are stored in the same computational nodes, whereas the pressure nodes are moved half a grid size from them. This approach greatly facilitates the implementation of the code and is computationally efficient as there is only a small amount of interpolation between the nodes. The staggering of the pressure nodes is sufficient to ensure a strong velocity-pressure coupling, which eliminates the well known pressure oscillations occurring on collocated meshes. Details of the derivative approximation and issues related to the interpolation between the velocity and pressure nodes are given in Tyliszczak (2014, 2016) and will not be repeated here. However, it needs to be mentioned that the applied interpolation has a smoothing effect which stabilises the solution but also slightly decreases the effective Reynolds number (Tyliszczak, 2014). Formally, it can be shown that this interpolation corresponds to a spatial filtering, which introduces some additional numerical dissipation. In case of the simulation in which the density of the computational mesh does not ensure full resolution of all small scale phenomena such an extra-dissipation plays a role of the sub-filter model. Actually, the solutions obtained in such situations should be regarded as the results of implicit LES computations.

The SAILOR code has been verified and validated both in problems with wall bounded flow domains and in free flows, including classical (Boguslawski et al., 2013; Wawrzak et al., 2015; Boguslawski et al., 2016) and excited jets and flames (Tyliszczak and Geurts, 2014, 2015; Tyliszczak, 2015a, 2015b). In all these cases, the SAILOR code turned out to be computationally very efficient and accurate. This is expected to carry over to the simulations performed in this paper as a complexity of the cases analyzed here is similar to the complexity of the problems studied previously.

3. Computational configuration

The Reynolds numbers of the consider circular jets are $\mathrm{Re} = 1 \times 10^3$, 3×10^3, 5×10^3, with $\mathrm{Re} = U_j D/\nu$ where U_j is the inlet centreline velocity, D - diameter of the jet nozzle, ν - kinematic viscosity. The flow set-up showing the jet nozzle together with a sketched excitation is presented in Fig. 1. In the present work, the inner geometry of the nozzle and forcing generators usually placed upstream of the inlet or at the nozzle edge are not taken into account. The analyzed domain is a simple rectangular box, which starts in the plane of the nozzle exit and covers the region $12D \times 16D \times 12D$. This size is found large enough to capture the main flow features with only small influence of the side boundaries. The presence of forcing is mimicked by the inlet velocity profile $U(\mathbf{x}, t)$ specified in terms of the mean velocity profile $U_0(\mathbf{x})$ to which forcing component is superimposed as:

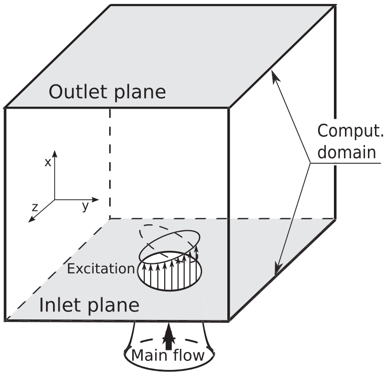

Fig. 1. Schematic view of the computational domain.