Numerical investigations on rectangular and circular synthetic jet impingement

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Abstract: Synthetic jets are produced by the oscillatory movement of a membrane inside a cavity, causing fluid to enter and leave through a small orifice. Under certain conditions, the advected vortices are too far to be ingested back and a jet is created. The present study is focused on investigating the differences between the flow of slotted and axisymmetric synthetic jets enclosed between two parallel plates, and impinging into a uniformly heated plate at a certain distance from the actuator orifice. The unsteady three-dimensional Navier-Stokes equations have been solved for Reynolds numbers of 50 and 500 under a jet formation criteria (JFC) of 3 using time-accurate numerical simulations. A detailed model based on an Arbitrary Lagrangian-Eulerian (ALE) formulation is used to account for the movement of the actuator membrane. The flows are noticeably different and are inherently three-dimensional. The axisymmetric configuration presents three different flow regions that have been identified according to the literature: the main vortex ring, the trailing jet and the potential core. On the other hand, the slotted configuration presents two clear vortices that undergo turbulent transition and eventually form the jet. A detailed analysis of the vortex trajectories has shown that the advected vortices on the axisymmetric configuration reach the impingement before their slotted counterparts. Moreover, distributions of turbulent kinetic energy at the expulsion and vortex swirl and shear strength have revealed that the axisymmetric jet is more concentrated near the jet centerline than the slotted jet. For these reasons, at the same jet ejection velocity and actuator geometry, synthetic jet formation on the axisymmetric configuration can occur at higher frequencies than on the slotted configuration.

Keywords: Synthetic Jet Actuator, Numerical Simulation, Vortex, LES, DNS, ALE.

1 Introduction

Synthetic Jet Actuators (SJAs) [1, 2, 3, 4] consist of a cavity with a mechanically moving diaphragm. Its actuation changes the cavity volume periodically, causing external fluid to enter and leave through a small orifice. Under certain conditions, the advected vortices are too far to be ingested back. If so, a train of vortices (and eventually a jet) is created without the addition of mass flow, allowing the transfer of kinetic energy and momentum to a fluid medium without the need of piping systems.

The formation and evolution of SJAs was investigated by Smith and Glezer [5]. The concept of stroke length $L_0$ was defined as the integral of the stream-wise velocity at the orifice exit $u_0$ over the ejection part of the cycle, which corresponds to the half of the actuation period $\tau$

$$L_0 = \int_0^{\tau/2} u_0(t) \, dt$$
from which a reference velocity $U_0 = L_0/\tau$ can be defined. It was found out that the evolution of the SJA flow near the orifice is dominated by its time-periodic formation and advection of vortices that roll-up and become part of the jet. It was also observed that their mean trajectory scales with the stroke length. A dimensionless stroke length $L_0/d$, where $d$ is the orifice diameter, was proposed to be one of the parameters that define the SJA flow [6] and corresponds to the inverse of the Strouhal number. The jet formation criteria (JFC)

$$JFC = \frac{1}{Sr} = \frac{Re}{Sk^2}$$

introduced by Utturkar and Holman [7, 8], where $Sr, Re$ and $Sk$ are the Strouhal, Reynolds and Stokes numbers based on a time and space averaged velocity $\overline{U}$ at the SJA exit during the expulsion stroke ($\overline{U} = 2U_0$). The difference between this jet formation criteria and the dimensionless stroke length is a constant, as is further discussed in this work. The formation of synthetic jets was analyzed for axisymmetric and two-dimensional configurations and notorious differences were found between them, even though the orifice geometry was similar. The dissimilar fluid flow solutions for the two configurations presented different critical values of a constant $K$ (0.16 and 2 for axisymmetric and two-dimensional configurations respectively) from which the JFC has to be bigger than in order for jet formation to occur. Moreover, as predicted by Utturkar and Holman, experimental investigations of SJA cavity [9] and orifice shape [10, 11] have been found to be influential on the synthetic jet performance.

The flow patterns, namely vortex rings for axisymmetric configurations and vortex dipoles for two-dimensional configurations, resulting from the interaction of the currents entering and leaving the cavity are substantially different and complex. Although many numerical analyses [12, 13] study the two-dimensional (or span-wise periodic) configuration, the axisymmetric configuration is preferred for industrial applications [14, 15, 16]. Many studies have been devoted to analyze the flow morphology of these two configurations, however, to the authors’ knowledge, few works have been focused on their comparison.

The flow behavior of axisymmetric impinging synthetic jets has been experimentally analyzed by Greco et. al. [17, 18]. Two different jet morphologies were observed in terms of the dimensionless stroke length. For low dimensionless stroke length or jet formation criteria ($4 \leq L_0/d < 8$ or $1.27 \leq JFC < 2.55$) the Strouhal number is high and the jet morphology consists of a succession of primary vortex rings, where the impingement is dominated by the vortex ring and results in a larger jet width and lower centerline velocity. On the other hand, at high dimensionless stroke lengths or jet formation criteria ($8 \leq L_0/d < 16$ or $2.55 \leq L_0/d < 5.09$) the Strouhal number is low and the flow is formed by a disconnected primary vortex ring followed by a trailing jet and a region of low turbulence, called potential core. In these flows, the trailing jet, which is formed of multiple vortex rings generated by the Kelvin-Helmholtz instability, becomes the most influential feature of the flow. This behavior and time scales are consistent with what was observed in vortex ring formation for steady jets [19]. In this context, it was observed that, in the case of a vortex ring followed by a trailing jet, the vortex ring reduced its circulation by shedding the excess vorticity into its wake.

The flow patterns of slotted synthetic jets were numerically analyzed by Kral and Donovan [2], where the SJA was successfully implemented as a suction/blowing boundary condition (thus avoiding any representation of the SJA cavity). The evolution and morphology of vortex dipoles was numerically analyzed by Kotapati et al. [12]. They performed span-wise periodic direct numerical simulations (DNS) using a simplified cavity model of the SJA previously analyzed with particle image velocimetry (PIV) by Yao et. al. [20] in the framework of the NASA LaRC Workshop (2004). The main vortex pairs that convect downstream by self-induction were successfully identified along with secondary stream-wise oriented rib-like structures surrounding the main vortex cores. It was found that these structures undergo amplification in the span-wise direction due to vortex stretching and cause the transition to turbulence of the main vortices in the vicinity of the orifice. Thus, a well-developed turbulent jet is eventually formed[12]. Experimental and numerical investigations of the impingement behavior and vortex merging of two-dimensional synthetic jets have been performed by Silva-Llanca et. al. [21, 22]. Different techniques for identifying coherent structures in synthetic jets were compared and the Q-criterion [23] was selected as a vortex presence indicator. Three stages of vortex merging were identified in two-dimensional impinging synthetic jets, in which the expelled vortex slowly merges with the remaining vortex of the previous actuator cycle. This phenomenon was found to be directly proportional to the Reynolds number and inversely proportional to the frequency. Moreover, secondary vortex rings were identified on the impingement plate and were found to have a major role in the
heat transfer performance of synthetic jets.

The aforementioned studies in which the synthetic jet impinges into a wall, consider an open configuration and the heated flow is not ingested back inside the actuator; hence the model in which the SJA outlet is assumed to be at a constant temperature is reasonable. Recent numerical studies of opened and enclosed configurations of an axisymmetric synthetic jet, using moving mesh techniques for the membrane description, have been performed by Hatami et. al. [24]. Noticeable differences were found in the flow and heat transfer capabilities between the enclosed and opened configurations. In particular, the advected vortices were found to stretch axially on the enclosed configuration whereas, in the opened configuration, they stretch radially. This has been found to produce more coherent vortices in the opened configuration compared with the enclosed configuration.

The present study, is devoted to a configuration where the jets are enclosed between two parallel plates. Under these circumstances, the external flow interacts with the flow inside the SJA cavity as it is ingested back inside the actuator; thus making the conditions at the actuator outlet hard to estimate. Therefore, a formulation that imposes the movement of the membrane position using Arbitrary Lagrangian-Eulerian (ALE) formulation is proposed to describe a canonical synthetic jet actuator geometry. This allows imposing physically realistic boundary conditions for the momentum and energy equations at the actuator membrane. The other closures that exist in the literature, for example, imposing an inlet velocity [12] or the velocity at the SJA outlet [13], would not be suitable for the present configuration. In addition, the present study is also devoted to understand the impact of the turbulence inside the cavity on the external flow and the impingement.

The aim of the current research is to understand and predict the cooling capabilities of confined synthetic jets; however, the present paper is focused on the description and comparison of the flow features of both SJAs. Hence, the objectives of this paper are: (i) To provide a better understanding of the synthetic jet flow enclosed between two parallel plates for both the span-wise periodic and axisymmetric configurations at Reynolds numbers of 50 and 500 by analyzing the vortices formed in the external and internal flow. (ii) To report the results of a detailed model of the SJA membrane movement using ALE techniques that allow to study the flow and heat transfer mechanism inside the actuator cavity, aiming to provide a better approximation of the flow and temperature at the SJA orifice. (iii) To provide insight on the difference between the flows of the slotted and axisymmetric configurations. Analyses of temperature distributions and Nusselt numbers are left as future work.

This paper is structured as follows: Firstly, the problem is presented followed by a description of the mathematical and numerical models, highlighting the formulation used for the membrane movement and performing a domain and grid sensitivity analysis. Then, the results are examined, starting with a study of the instantaneous flow evolution and an analysis of its temporal spectrum to figure out the dominant frequencies of the flow. This is followed by an investigation of the time and phase averaged flow to illustrate the main structures of the flows and compare two configurations analyzed.

## 2 Problem Statement and Mathematical Model

The present work is devoted to the analysis of two different actuator configurations: a simplified rectangular actuator in an homogeneous domain in the $x_3$ direction (henceforth slotted configuration) and a simplified circular actuator (or axisymmetric configuration) as shown in Figure 1. Both jets impinge on a uniformly heated wall located at a orifice-to-surface distance $H/d = 5$, imposed based on the optimal distances for cooling applications [14, 21, 25], causing convective heat transfer from the wall to the jet. For both actuators, the dimensionless actuator cavity width $W/d$ is set to impose a jet formation criteria of 3. The other dimensions of the SJA are selected as in Liu [26], with $b/d = 0.3$ and $B/d = 1.67$. For the slotted configuration, a depth of $D/d = 6$ is considered to allow the full development of the three-dimensional flow.

The Navier-Stokes and energy equations are used to model the flow. Incompressible regime is assumed since the ratio between the Helmholtz frequency of the actuator and the drive frequency os assumed to be less than 0.5 [27, 9]. The present study focuses on situations where the jet velocity is high enough to disregard natural convection, i.e., the Richardson ($\text{Ri}$) number, defined as the ratio of the buoyancy term to the flow shear term, is low enough. Experimental and numerical studies [28] show that buoyancy effects become relevant for Richardson $\text{Ri} > 0.01$. Also, for the present work, thermal radiation is neglected. Under
these assumptions, the incompressible Navier-Stokes equations are

\[
\frac{\partial u_j}{\partial x_j} = 0 \tag{1}
\]

\[
\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \tag{2}
\]

\[
\frac{\partial T}{\partial t} + \frac{\partial (u_i T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{k}{\rho c_p} \frac{\partial T}{\partial x_j} \right) \tag{3}
\]

where \(x_i\) are the spatial coordinates (or \(x, y\) and \(z\)), \(u_i\) are the cross-stream, stream-wise and span-wise velocity components (or \(u, v, w\)), \(p\) is the pressure and \(T\) is the temperature. \(\rho\) is the density, \(\nu\) is the kinematic viscosity, \(c_p\) is the specific heat coefficient at constant pressure and \(k\) is the thermal conductivity of the fluid.

The Reynolds number is defined along the standard set by Smith and Glezer [5] as

\[
Re = \frac{U_0 d}{\nu} \tag{4}
\]

where \(d\) is the orifice diameter (see Figure 1) and \(U_0\) is a characteristic velocity defined in terms of the stroke length \(L_0\) as \(U_0 = L_0 f_0\), and \(f_0\) is the SJA membrane oscillating frequency. In turn, the stroke length is defined as

\[
L_0 = \frac{1}{S_d} \int_0^{\tau/2} \int_{S_d} u_2(x, 0, z, t) dS \, dt \tag{5}
\]

where \(S_d\) is the actuator outlet surface and \(\tau\) is the period. The Prandtl number is \(Pr = (\rho \nu c_p)/k\) and takes an assumed value of 0.71, whereas the Strouhal number \(Sr\) is

\[
Sr = \frac{2 \pi f_0 d}{U_0} \tag{6}
\]

As an alternative to the Strouhal number, some authors [7, 12, 21] define the Stokes number as

\[
Sk = \sqrt{\frac{2 \pi f_0 d^2}{\nu}} \tag{7}
\]

that can also be used to characterize the flow. The relationship between Reynolds, Strouhal and Stokes
numbers is given by the jet formation criteria (JFC). For the geometries considered in the present work, if the JFC is lower than an approximated value of 0.16 for the circular geometry and 2 for the span-wise periodic rectangular geometry, the jet is not formed.

In the present work the actuator membrane position is modeled as

$$x_2 = -\delta(x_1, x_3) \cos (2\pi f_0 t)$$

(5)

where \(\delta(x_1, x_3)\) is a shape function. A mean amplitude can be defined as

$$A = \frac{1}{S_W} \int_{S_W} \delta(x_1, x_3) dS$$

where \(S_W\) is the surface of the actuator membrane (see Figure 1). Then, the characteristic velocity \(U_0\) can be related to the mean amplitude and the drive frequency \(U_0 = 2\overline{A} f_0 S_W / S_d\), thus coupling \(f_0\) and \(U_0\). Therefore, a dimensionless stroke length is obtained by integrating Equation (4) as

$$L_0 d = 2 \overline{A} \left( \frac{S_W}{S_d} \right)$$

(6)

Also, under this definition, the jet formation criteria becomes a purely geometrical parameter.

$$JFC = \frac{2}{\pi} \left( \frac{\overline{A}}{d} \right) \left( \frac{S_W}{S_d} \right)$$

(7)

Therefore, as seen by Smith and Glezer [5], when the motion of the actuator membrane is time-harmonic, the formation parameters of the jet depend only on the amplitude of the actuator, and cannot be varied independently. Moreover, the relationship between JFC and the dimensionless stroke length is \(L_0 / d = \pi JFC\).

The present work is based on keeping JFC at a constant value of \(JFC = 3\) and focusing on the effects of the Reynolds number. This implies that, according to Equation (7), \(W/d\) must differ for both actuators as \(S_W / S_d\) is different for each configuration considered. In fact, the actuator width for the slotted configuration must be greater than the actuator width for the axisymmetric configuration in order to achieve \(JFC = 3\).

2.1 Numerical Model

The Reynolds numbers considered are \(Re = 50\) and 500. For \(Re = 50\), DNS are performed, whereas, for \(Re = 500\), simulations are carried out using Large-Eddy Simulations and the filtered equations are used instead

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = 0$$

(8)

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{T})}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \frac{\nu}{\rho \partial x_i} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \right] - \frac{1}{\rho} \frac{\partial T_{ij}}{\partial x_j}$$

(9)

$$\frac{\partial \tilde{T}}{\partial t} + \frac{\partial (\tilde{u}_j \tilde{T})}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{k}{\rho c_p \partial x_j} \right) - \frac{1}{\rho c_p} \frac{\partial Q_i}{\partial x_j}$$

(10)

where \(\tilde{\text{•}}\) denotes the filtered magnitudes. The equations above include the sub-grid scale (SGS) stress tensor

$$T_{ij} = 2\nu \tilde{S}_{ij} \quad \tilde{S}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right)$$

which is the deformation tensor of the resolved field and the scalar flux is modeled using a gradient diffusion approach [29]

$$Q_i = \rho \frac{\nu c_p}{Pr_i} \frac{\partial \tilde{T}}{\partial x_j}$$

(11)
where $Pr_t$ is the turbulent Prandtl number. The present work uses the wall-adapting local eddy viscosity model (WALE) proposed by Nicoud and Ducros [30]

$$
\nu_t = (C_w \Delta)^2 \frac{\left(\frac{V_{ij} V_{ij}}{S_{ij} S_{ij}}\right)^{3/2} + (V_{ij} V_{ij})^{5/4}}{(S_{ij} S_{ij})^{5/2}}
$$

(12)

$$
V_{ij} = \frac{1}{2} \left( \bar{g}_{ij}^2 + \bar{g}_{ji}^2 \right) - \frac{1}{3} \delta_{ij} \bar{g}_{kk}^2
$$

where $\Delta$ denotes the cell volume, $C_w = 0.5$ the model constant and $\delta_{ij}$ the Kronecker delta. The symbol $\bar{g}$ corresponds to the velocity gradient tensor

$$
\bar{g} = \frac{\partial \tilde{u}_i}{\partial x_j}
$$

and $\bar{g}_{ij}^2 = \bar{g}_{kk} \bar{g}_{kj}$. This SGS model accounts for the effects of the strain and rotation rates as well as an appropriate near wall scaling for the eddy viscosity. From this point onwards, the relevant magnitudes will be expressed in dimensionless form where $\tilde{x}_i = x_i/d$ is the dimensionless spatial coordinates, $\tilde{u}_i = u_i/U_0$ is the dimensionless velocity and $\tilde{T} = (T - T_\infty)/(T_{wall} - T_\infty)$ is the dimensionless temperature where $T_{wall}$ and $T_\infty$ denote the temperature at the heated wall and the bulk temperature, respectively.

For both configurations, non-slip boundary conditions are imposed at the top ($\tilde{x}_2 = H/d$) and bottom ($\tilde{x}_2 = 0$) of the discharge cavity as well as at the actuator walls including the SJA actuator membrane ($\tilde{x}_2 < 0$). Free-flow boundary conditions are prescribed at all the vertical boundaries with $\tilde{x}_2 > 0$. Regarding the energy equation, the cavity top wall is hot ($\tilde{T} = 1$) and the bottom wall is cold ($\tilde{T} = 0$). The lateral boundaries are considered adiabatic ($\partial \tilde{T} / \partial n = 0$). The SJA walls ($\tilde{x}_2 < 0$) are assumed to be cold. Moreover, for the slotted configuration, periodic boundary conditions are set between the front ($\tilde{x}_3 = 0$) and back ($\tilde{x}_3 = D/d$) faces. The SJA membrane movement has been modeled using an ALE formulation with Equation (5) and $\delta(x_1, x_3) = \delta_C \cos(\pi r/W)$, where $r = x_1$ and $r = \sqrt{(x_1^2 + x_3^2)}$ for the slotted and axisymmetric configuration, respectively. In this formulation, $\delta_C$ is a scaling parameter used to set a certain value for $\overline{A}$ and $W$.

Statistically accurate representations of the flow are needed in order to understand the SJA flow. However, the overall system contains very slow temporal scales related with the low velocity zones, despite the intense mixing in the jet vicinity. This results in a very large computational time for the flow to reach statistical stationary conditions (typical numbers are on the order of 200 cycles). For this reason, the flow has been initialized using precursory DNS (for $Re = 50$) or URANS (for $Re = 500$) simulations using the $k - \omega$ SST [31] model with a large time-step in order to reduce the computational time. With this strategy the statistical stationary state is reached within 20 actuator cycles. Moreover, the initial conditions for the finer meshes are generated from the solution obtained with coarser grids, which in turn reduces the initial transient by 5 cycles. Once the statistical stationary state is reached, the simulations are run for 20 actuator cycles, using the last 15 to obtain relevant time and phase averages of the flow and the Nusselt number.

This work is performed in the framework of collaboration between STFC Daresbury Laboratory, Barcelona Supercomputing Center and the Aerospace Section of Universitat Politècnica de Catalunya, therefore the parallel multi-physics code Alya [32] and the parallel computational fluid dynamics code Code_Saturne [33] are used to compute the solution field for the fluid and its thermal interaction with the hot wall. Both codes are designed for large-scale parallel applications [34, 35]. Alya is based on the Finite Element method, using a fractional step approach to solve the pressure-velocity coupling and an explicit fourth-order Runge-Kutta time integration scheme. Code_Saturne is based on the Finite Volume method, also using a fractional step to solve the pressure-velocity with a second-order centered scheme as spatial discretization and an implicit second-order Crank-Nicholson time integration scheme.

### 2.2 Appropriateness of the domain and grid sensitivity analysis

Two similar strategies have been used to design the computational grids: (i) The slotted configuration grid is built by extruding a two-dimensional grid along the $x_3$ axis for a certain number of planes and a fixed depth of $\tilde{x}_3 = 6$. (ii) The axisymmetric configuration grid is created by the revolution of a two-dimensional
grid along the \( x_2 \) axis for a certain number of angular divisions. A detail of the computational grids for both configurations is presented in Figure 2. Successive grids have been constructed by multiplying the two-dimensional generator grid. The coarsest grid considered (for \( Re = 50 \)) has 350,000 control volumes (CV); whereas the finer grids considered (for \( Re = 500 \)) have 4.0 and 5.0 million CV.

Grid convergence studies have been carried out for each of the Reynolds numbers considered. As an example, Figure 3 shows the grid study for \( Re = 500 \) and both configurations. The span-wise and phase averaged vertical velocity profiles at different heights are compared for the grids considered, achieving good agreement with minimal differences at the points of maximum and minimum span-wise velocity.

Moreover, for the slotted configuration, the computational domain in the span-wise direction has been designed so as to contain the largest scales of the flow. Span-wise two point correlations are used to verify if the assumed size is correct for all Reynolds numbers considered in this work. They are defined as

\[
R_{ii} = \frac{u_i'(x_i, t)u_i'(x_i + \delta, t)}{u_i'^2}
\]

(13)

where \( \tau \) denotes a time average and \( u_i' = u_i - \overline{u}_i \). The values for the two point correlation must tend towards zero for the turbulent cases as they approach the half-size of the domain. Figure 4 illustrates the span-wise two point correlations for \( u_3'u_3' \) at \( \tilde{x}_1 = 0 \) and \( \tilde{x}_2 = 2.5 \) for all the Reynolds numbers considered in this study. This position has been selected as a representative point where the jet scales have been fully developed. As seen in the figure, all correlations approach zero at the domain half size, thus the domain is wide enough to contain the largest and more energetic scales, except for \( Re = 50 \). This could indicate the presence of
Figure 3: Span-wise and time-averaged vertical velocity at different heights ($\hat{x}_2 = 0.5$, $\hat{x}_2 = 2.5$ and $\hat{x}_2 = 4.5$, each shifted 0.7 units upwards) for $Re = 500$; blue: coarse grid; red: mid-size grid; yellow: fine grid. (a) Slotted configuration; (b) axisymmetric configuration.

quasi-laminar structures and a larger domain would be needed. However, $W/d = 6$ has been maintained for $Re = 50$ as a good compromise in terms of computational time.

Figure 4: Two point correlation for $u_3'u_3'$ and different Reynolds numbers.

3 Results and Discussion

The flow on a synthetic jet is very complex and its morphology is highly influenced by the JFC and its geometry. Vortices roll up from the actuator lips and move upwards, until the impingement into the top wall is reached.

3.1 Instantaneous Flow

The flow at $Re = 50$ is represented in Figure 5 for a typical instant. The vortical structures have been identified by means of Q-isocontours [36] where $Q$ is the second invariant of the velocity gradient tensor and is defined as

$$Q = -\frac{1}{2} \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i}$$  \hspace{1cm} (14)
The condition $Q > 0$ has been found to be effective in identifying regions of coherent vorticity [22, 23]. The flow is laminar for both configurations at $Re = 50$. While for the slotted configuration is clearly three-dimensional, the axisymmetric flow is almost two-dimensional except for some structures that are generated at the impingement (not visible in this frame). The trailing jet observed for high JFC synthetic jets is not visible as $Re$ is too low and the Kelvin-Helmholtz instability is not triggered.

Figure 5: $Q$-isocontours ($Q = 0.1$) colored by the dimensionless velocity magnitude at $t = \tau/4$ for the slotted (left-hand side) and axisymmetric (right-hand side) configuration at $Re = 50$.

The flow at $Re = 500$ has a more interesting behaviour. Typical instantaneous vortical structures are represented in Figure 6. Four different instants (or phases) are illustrated: Figure 6 (a) and (c) are the maximum expulsion ($t = 0$) and maximum ingestion ($t = \tau/2$) phases, while Figure 6 (b) and (d) are the maximum positive ($t = \tau/4$) and negative ($t = 3\tau/4$) membrane displacement phases. A large amount of vortical structures can be observed in the flow for $Re = 500$, mostly concentrated in the zones near the orifice, both outside and inside the synthetic jet actuator cavity. During the ejection stroke, cold fluid is expelled from the actuator orifice and reaches the top wall at about $t = \tau/4$ (Figure 6 (b)). Then, the heated fluid is taken inside the actuator during the suction stroke ($t = 3\tau/4$), where it is cooled before being ejected again (Figure 6 (d)). Noticeable differences can be observed between the flow of the two configurations. The flow of the axisymmetric configuration starts with a main vortex ring at about $\bar{x}_2 = 2.5$ (Figure 6 (a), right) being advected downstream from the actuator orifice and reaching the impingement without losing its coherence (Figure 6 (b), right). Along with the main ring, a number of small structures formed by the Kelvin-Helmholtz instability can be seen as well as a region of low turbulence in the vicinity of the orifice, the potential core (Figure 6 (b), right). Vortex separation (pinch-off) [19] is observable between the main vortex ring and the trailing jet, although both have reached the impingement and spread through the heated wall during the suction part of the cycle (Figure 6 (c), right). The main vortex ring is persistent enough to be still visible at the start of the next expulsion part of the cycle (Figure 6 (d,a), right). This jet morphology is characteristic of jets with high JFC and is consistent with what has been observed in the literature for continuous and synthetic jets [18, 19, 37].

Regarding the slotted configuration, the vortex dipoles roll-up from the orifice and almost lose all coherence due to the interaction with the smaller structures and the vortex stretching (Figure 6 (a), left). This creates a jet that advects downstream until the impingement is reached (Figure 6 (b), left). During the suction part of the cycle, some of these structures are ingested back inside the actuator cavity (Figure 6 (c), left). Moreover, there is no noticeable potential core as it is seen in the axisymmetric configuration. This jet morphology and behavior are also consistent with what is observed for two- and three-dimensional slotted synthetic jets [12, 22].

Due to the temporal scales associated with the low velocity zones, it is interesting to identify the frequencies related to these zones as they have an impact on the averaged flow statistics. To do so, a set of numerical probes have been located at different zones of the domain and the signal of the independent variables has been recorded during the entire simulation. These numerical probes are located in the following matrix: $\bar{x}_1 = 0$, 5, and 10, $\bar{x}_2 = 0$, 2.5, and 4.5 and for each plane in the $\bar{x}_3$ or angular direction.

The spectrum of the stream-wise velocity of some of these numerical probes is analyzed in Figure 7. As it can be seen, the centerline flow ($x_1 = 0$) is mostly dominated by the periodicity of the ejection and
Figure 6: Q-isocontours ($Q = 1.0$) colored by the dimensionless velocity magnitude at different phase instants for the slotted (left-hand side) and axisymmetric (right-hand side) configuration at $Re = 500$. (a) phase $t = 0$; (b) $t = \tau/4$; (c) $t = \tau/2$; (d) $t = 3\tau/4$. 
suction events in both configurations, marked in the figures as driving frequency. When comparing the energy contained in this peak for both configurations, it can be seen that it is higher for the axisymmetric configuration. Notice that in both configurations, the spectra also contain harmonics of the main peak, at frequencies $2f/f_0$, $3f/f_0$ and further for the axisymmetric configuration, corresponding to the vortices created by the Kelvin-Helmholtz instability. The footprint of the cyclic ejection/suction event can still be observed when the flow away from the jet centerline is inspected, yet the energy contained in the peaks is decreased. Notice that the energy contained in the peaks for the axisymmetric configuration away from the centerline are much lower than the energy contained in the slotted configuration. Moreover, a broadband low-frequency signal, also marked in the figures, can be seen for both configurations corresponding to the slow motion of the largest scales of the flow. This peak is centered around $f = 0.0075$ for $Re = 500$, which roughly corresponds to approximately 7 actuator cycles. These frequencies are also related with the vibration frequencies of the larger structures that have been identified in the flow, as will be later seen. Moreover, as a result of this low-frequency motion, well-converged statistics of the flow far from the jet centerline require a longer time integration of at least a few slow-motion full cycles. In addition, these frequencies are independent of the geometry studied and are mostly influenced by the $Re$ and $Sk$ numbers (or JFC) selected.

![Energy spectrum](image)

Figure 7: Energy spectrum of different probes at $Re = 500$ for the stream-wise velocity. Probe locations are: left-hand side $\tilde{x}_1 = 0, \tilde{x}_2 = 2.5$; right-hand side $\tilde{x}_1 = 5, \tilde{x}_2 = 2.5$. (a) Slotted configuration; (b) axisymmetric configuration.

### 3.2 Time and Phase Averaged Flow

Time and phase averaged magnitudes are computed by averaging the last 20 actuator cycles in order to obtain time-accurate statistics. The major vortices have been identified and are displayed in Figure 8 for
Re = 500 and the two studied configurations. They have been identified using velocity streamlines and with regions where Q > 0, which correspond to the shadowed grey areas.

Figure 8: Time averaged velocity streamlines for Re = 500 with the regions with Q > 0 highlighted in the background (right-hand side of the computational domain). (a) Slotted configuration; (b) axisymmetric configuration.

In the slotted configuration, two large clock-wise and counter clock-wise vortices (θ1 and θ2 respectively) dominate the external flow field. The former is the result of the coalescence of the vortices ejected from the actuator lips while the latter is characteristic of the enclosed configuration and is not present in the open configurations, e.g., of Silva-Llanca [22]. The axisymmetric configuration also has the clock-wise rotating vortex θ1, albeit it appears much smaller than the slotted counterpart. Another major vortex appears, denoted as θ0, and corresponds to the impinging main vortex of the previous cycle, as it will be further seen. This vortex differs from θ2 in the sense that θ2 appears due to the interaction of the flow far from the jet centerline with the bottom wall. Moreover, the potential core and the trailing jet are visible in the vicinity of the jet centerline in the axisymmetric configuration, but are not present in the slotted configuration. The time-averaged flow inside the SJA is also different for both configurations. While in the slotted configuration, two vortices appear side by side, in the axisymmetric configuration there is one big vortex. This phenomenon is due to the difference in width of the cavities, which is being imposed by the JFC.

McGuinn et. al. [37] presented visualizations of impinging synthetic jets for different JFC on PIV data by using a parameter (s) that allows for an efficient identification of the vortex trajectories. It enables to characterize the strength of a synthetic jet vortex ring and to quantify the swirling and shearing strength of a vortex. It is defined as the negative value of the discriminant of complex eigenvalues of the local velocity gradient tensor [38], i.e.,

\[
s = -\frac{1}{4}\left(\frac{\partial \bar{u}_1}{\partial x_1}\right)^2 + \left(\frac{\partial \bar{u}_2}{\partial x_2}\right)^2 + \frac{1}{2}\frac{\partial \bar{u}_1}{\partial x_1}\frac{\partial \bar{u}_2}{\partial x_2} - \frac{\partial \bar{u}_1}{\partial x_1}\frac{\partial \bar{u}_2}{\partial x_2}\frac{\partial \bar{u}_1}{\partial x_2}\frac{\partial \bar{u}_2}{\partial x_1}
\]

and allows to disregard much of the weaker turbulent vorticity. This parameter has been used in the present work to compare the time averaged flow of both configurations in Figure 9. The difference of the jet morphology for the two configurations studied is again stressed: the slotted configuration has a wide structure that corresponds to the coalescence of the expelled vortices with a wide vortex path, whereas the axisymmetric configuration has narrower vortex path that becomes wider at the impingement. This has been identified due to the higher velocity of the fluid in the trailing jet that impacts upon the vortex and is in good agreement with what has been observed for high JFC synthetic jets [18, 37]. These effects have implications in the jet width as it will be further discussed.

The dynamics of the flow can be better detected when the phase averaged flow is inspected. Figure 10 shows the major vortices, Θ0 and Θ1 following the convention set by Silva-Llanca [22], that have been identified for the phase averaged flow using velocity streamlines and highlighting the regions of Q > 0. During the ejection stroke (Figure 10 (a), t = 0), a vortex rolls-up from the actuator orifice and is advected
downstream on both configurations. Another vortex, Θ₀, is also present and corresponds to the advected vortex of the previous cycle. The advected vortex Θ₁ is seen to interact with Θ₀ in the slotted configuration, whereas it reaches the impingement unperturbed in the axisymmetric configuration (Figure 10 (b), t = τ/4). Notice also the trailing jet area at the vicinity of the jet centerline (Figure 10 (b), right) that reaches the impingement along with the main vortex Θ₁. An additional vortical structure (Θ₂) is created near the impingement point only for the slotted configuration when the suction stroke begins (Figure 10 (c), t = τ/2). It sweeps the surface from left to right until about \( \bar{x}_1 = 6 \) and then merges with another structure (Θ₂), which is particular of the enclosed configuration (Figure 10 (d), left). The vortex Θ₄ has been identified as the main heat transfer enhancement mechanism for slotted jets in the near wall region in open configurations [14, 22]. Nonetheless, the dynamics of the axisymmetric configuration are significantly different. Following the impingement and during the suction part of the cycle, the vortex Θ₁ sweeps the surface until about \( \bar{x}_1 = 3 \), with the effect of the trailing jet mostly seen until about \( \bar{x}_1 = 1 \) (Figure 10 (c), right). As the vortex Θ₁ sweeps the impingement surface, it starts to lose coherence and eventually separates from the impingement area. At the start of the next expulsion cycle (Figure 10 (a), t = 0), Θ₁ becomes Θ₀ and the dynamics repeat themselves. Vortex dynamics of the axisymmetric configuration depicts a clear contrast with the dynamics of the slotted configuration. In the former, no mixing between Θ₁ and Θ₀ is observed nor the appearance of Θ₂, in contrast to what is observed in the latter.

The spatial distribution of the turbulent kinetic energy \( k \) at the expulsion stroke (t = 0) is plotted in Figure 11. The turbulent kinetic energy \( k \) is defined as half of the trace of the Reynolds stress tensor

\[
k = \frac{1}{2} < u'_i u'_j >
\]

where \( < \cdot > \) denotes a phase average and \( u'_j = u_i - < u_i > \). The different jet morphologies from both configurations are again emphasized. The jet formed in the slotted configuration is clearly of turbulent nature, starting in the region of the orifice at \( \bar{x}_1 = 0.5 \), where vortex stretching starts to occur, up to \( \bar{x}_2 = 2 \). Also, notice a certain widening as the energy is being transported downstream towards the impingement. On the other hand, the jet formed in the axisymmetric configuration concentrates its turbulent energy on the trailing jet that rises from the actuator lips to the position of the main vortex ring. Moreover, it has lower turbulence levels that are more concentrated in the region of the actuator orifice (\( \bar{x}_1 = 0.5 \)), in contrast to its slotted counterpart. In addition, a zone of low turbulent kinetic energy near the jet centerline on the axisymmetric configuration that corresponds to the potential core is also observed.

The temporal evolution of the vertical position of the aforementioned Θ₁ vortex is plotted in Figure 12 for both configurations to further analyze the vortex dynamics. It can be seen that, for the axisymmetric configuration, the impingement is reached at \( t/\tau \approx 0.4 \), whereas for the slotted configuration it occurs at \( t/\tau \approx 0.5 \). This is due to the vortex Θ₁ being delayed by the interaction with Θ₀, which occurs at about \( t/\tau \approx 0.4 \) only for the slotted configuration. The vortex Θ₁ remains at \( \bar{x}_2 > 4 \) as it sweeps the impingement surface until it loses all its coherence on the axisymmetric configuration, while Θ₁ merges with Θ₀ and

Figure 9: Time-averaged distributions of the swirl and shear strength parameter \( s \) (Equation (15), right-hand side of the computational domain). (a) Slotted configuration; (b) axisymmetric configuration.
Figure 10: Phase averaged velocity streamlines for $Re = 500$ with the regions with $Q > 0$ highlighted in the background (right-hand side of the computational domain). Left-hand side: slotted configuration; right-hand side: axisymmetric configuration; (a) phase $t = 0$; (b) $t = \tau/4$; (c) $t = \tau/2$; (d) $t = 3\tau/4$. 
remains at $\tilde{x}_2 \approx 3$ on the slotted configuration. As a result, the vortex $\Theta_1$ in the axisymmetric configuration reaches the impingement surface before the slotted one. This has an impact on the jet formation, which is defined as an outward velocity along the jet axis that corresponds to the generation and escape of a vortex ring [8]. Under this definition and in the light of the data in Figure 12, the reason why the axisymmetric configuration allows lower JFC than the slotted configuration is the aforementioned difference between the velocity of the advected vortices in the two configurations. At the same jet ejection velocity and orifice diameter, the formation of vortex rings of the axisymmetric configuration can occur at higher frequencies than the formation of vortex dipoles of the slotted configuration.

Another important jet parameter to analyze is the jet half-width or wake. It is defined as the distance from the centerline where the velocity deficit has decayed to one-half of its maximum value and is represented in Figure 13 for both configurations studied. As it can be seen, the slotted configuration jet is wider than its counterpart on the axisymmetric configuration. This is again due to the morphology of the vortex rings and vortex dipoles. In summary: (a) The jet in the axisymmetric configuration is more concentrated on the jet centerline compared with its slotted counterpart, where an interaction between the vortices $\Theta_0$ and $\Theta_1$ is observed. This results in a wider jet on the slotted configuration. (b) The vortices on the axisymmetric configuration reach the impingement before the slotted ones, which results in a more abrupt change of width slope in the jet upper part (as a result of $\Theta_1$ or $\Theta_s$ sweeping the impingement surface). (c) The effect of the vortex shedding on the main structures at the vicinity of the orifice and the higher turbulence levels cause a widening of the jet on the slotted configuration, which is not observed in the axisymmetric configuration. (d) The jet width of the slotted configuration increases with $Re$ as a result of an increased mixing between $\Theta_0$ and $\Theta_1$. On the axisymmetric configuration, it is similar for both $Re$ as the main vortex ring does not
lose its coherence until after the impingement. Notice that the zone up to $\tilde{x}_2 = 1$ for $Re = 50$, the jet widths of the slotted and axisymmetric configurations are equal. This is due to laminar vortices being advected from the orifice in both configurations that undergo equal trajectories.

4 Conclusions

Two different synthetic jet configurations, a slotted actuator and an axisymmetric actuator, enclosed between two large parallel plates and impinging into a plate have been studied for $Re = 50$ and 500. At $Re = 50$ DNS of the flow have been performed, while at $Re = 500$ LES have been carried out and the WALE model has been selected as closure for the SGS viscosity. A fixed JFC = 3 has been considered for all of the studied cases. The proposed formulation accounts for the time-periodic movement of the SJA membrane using ALE, therefore, the actuator frequency $f_0$ and velocity $U_0$ are coupled and the jet formation criteria becomes a geometrical parameter that depends on the actuator and orifice surfaces. Moreover, this formulation allows for a detailed study both inside and outside the actuator cavity and to obtain an accurate representation of the velocity and temperature at the SJA outlet. A simplified rectangular actuator in an homogeneous domain in the $x_3$ direction and a simplified axisymmetric actuator have been studied with a orifice to cavity height of $H/d = 5$. The resulting flows are quite complex, and a large number of actuator cycles has to be integrated in order to reach a statistically stationary state. Moreover, it has been found that, for both configurations studied, the far flow field is dominated by frequencies about 7 times lower than the driving frequency, resulting in the overall system having slow temporal scales. In addition, it is confirmed that an ALE model is needed in order to obtain an accurate representation of the SJA cavity for both configurations. The flows studied are inherently three dimensional, even for $Re = 50$, which has an effect on the jet characteristics and the size of the vortices. The differences on the jet morphology of the two studied configurations have been thoroughly identified by means of the Q-criterion and the swirling and shearing strength parameter. The external flow of the slotted configuration is dominated by two major vortices, $\vartheta_1$ and $\vartheta_2$, where the former is the result of the coalescence of the vortices expelled by the actuator and the latter is particular of the enclosed configuration. The axisymmetric configuration also shows the $\vartheta_1$ vortex but also another vortex, $\vartheta_0$, that corresponds to the impinging vortex of the previous cycle. In addition, the external flow of the axisymmetric configuration is also dominated by the trailing jet and the potential core. The vortex dipoles of the slotted configuration have been found to lose coherence early at the roll-up stage, thus creating a highly turbulent jet that advects downstream towards the impingement while it widens on the cross-stream direction. On the other hand, the vortex rings in the axisymmetric configuration are able to maintain their coherence, even after the impingement. The trailing jet contains most of the turbulent energy of the jet; however, it is lower than in the slotted configuration, which results in less jet widening and

![Graph](image_url)
vortex interaction.

The analysis of the position of the vortices advected from the actuator orifice on both configurations yields that the vortex on the axisymmetric configuration reach the impingement area before their slotted counterparts. This is due to the interaction of the vortex advected from the orifice, $\Theta_1$ with the vortex expelled on the previous cycle $\Theta_0$. Such interaction delays the downstream motion of $\Theta_1$ and occurs in the slotted configuration. This is in good agreement with the axisymmetric SJA having a lower critical JFC than the slotted SJA. These vortex dynamics are expected to have implications in the heat transfer performance of both configurations, which will be the subject of future works.

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**References**


