Large eddy simulation of a partially-confined triangular jet with self-excited low-frequency oscillation

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Abstract
This paper reports large eddy simulation (LES) of a self-excited oscillating jet issuing initially from a small triangular orifice into a circular chamber. The case simulated is that measured experimentally by England et al. (Exps. Fluids 48, 2010, pp. 69-80). Present calculations agree well with previous measurements.

It is found that a jet from the triangular orifice discharges into the chamber, re-attaches the inner wall and oscillates roughly gyroscopically about the chamber axis. In the mean sense, the jet exhibits axis-switching in its cross-section and rotates by 180° over a downstream distance of \( x = 0.5D \) (chamber diameter). Importantly, three strong longitudinal vortices occur in conjunction with the exit triangle sides, interacting with the central jet and also surroundings, at \( x/D \leq 1 \). These three vortices appear to merge as a larger one around the location where the unmixed core region is ended. Evidently as well, some ambient fluid outside is induced into the chamber and dashes upstream together with the reversed jet fluid, forming a secondary surrounding flow swirling in the opposite sense to the oscillation.

Introduction
A small flow ejecting into a relatively large specific chamber can produce large-scale low-frequency oscillations — this flow is complex and termed as a self-excited oscillating jet. Compared with simple, non-oscillating, free jets, e.g. round or triangular jets, the self-excited oscillating jet produces greater spreading rate, higher velocity decay rate and larger-scale velocity fluctuations which are all a source of large-scale turbulent mixing [1-5]. Such flows may be used to improve the performance of industrial burners, multi media mixers and reactors in the processing industry. For example, the self-excited precessing jet (PJ) devices [1] and new generation oscillating-jet devices [2] have been beneficially installed at cement, glass and lime kilns.

In early studies with a circular orifice, Nathan et al. [3] showed that, for the PJ to oscillate reliably, the chamber inlet-expansion ratio must be larger than about 5.0, i.e. \( D/d_{ch} > 5 \) (see Fig. 1 for notations), and the length ratio of the chamber must be in the range of \( 2.6 \leq L/D \leq 2.8 \). A small lip of height \( h_1 = (D - d_2)/2 \leq 0.1D \) is usually attached to the chamber exit. Measurements and observations of the PJ flow [4, 5] show that the Strouhal number of the precession has a significant influence on the oscillating mixing field, while the Reynolds number does not.

Mi et al. [2] then found that the non-circular orifice can enhance the oscillation process, relative to the circular inlet case. In particular, the use of the triangular inlet is one of the best options for this enhancement. In a parametric study of the oscillating triangular jet (OTJ) nozzle, Lee et al. [6, 7] found that the spreading angle of the OTJ flow from the nozzle is significantly smaller than that of the PJ flow and it varies more gradually over broad ranges of the ratios \( L/D \) and \( D/d_{ch} \). A designer therefore has the flexibility not only to accommodate a much lower supply pressure but also to choose the jet spreading angle. England et al. [8] investigated the effect of the density ratio of the OTJ fluid to ambient fluid on the resulting OTJ flow downstream from the nozzle. The initial spread and decay of the emerging jet were found to depend upon the density ratio while the dominant oscillation frequency decreases with increasing the density ratio.

However, the OTJ flow is highly unsteady and complex, and so the detailed information on the instantaneous flow structure inside the chamber is still lacking. This makes it difficult to understand the formation mechanism of the oscillation. The present work is part of the study that aims to eventually address this deficit. We use Large Eddy Simulation (LES) to visualize the OTJ flow structure. Note that the LES can provide the quantitative detail of the whole flow, which remains impossible by experiments. To our best knowledge, it is the first time to study the OTJ flow by LES.

Following the experimental investigation by England et al. [8] on the OTJ flow, the present study is aimed at examining both the mean and instantaneous OTJ flow structures mainly inside the chamber under the same initial and boundary conditions. The simulation was performed for the same Reynolds number as used in [8], i.e., \( Re_D = 17,900 \), where \( Re_D = U_d/d_2/\nu \) with \( U_d \) being the mass-averaged velocity at the orifice-inlet, \( d_2 \) the orifice equivalent diameter and \( \nu \) the kinematic viscosity of the fluid.

Computational details
The filtered governing equations of an unsteady incompressible viscous flow for LES are

\[
\begin{align*}
\frac{\partial \overline{\mathbf{u}_i}}{\partial t} + \frac{\partial \overline{\mathbf{u}_i} \overline{\mathbf{u}_j}}{\partial x_j} &= -\frac{\partial \overline{p}}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \left( \frac{\partial \overline{\mathbf{u}_i}}{\partial x_j} \right) - \frac{\partial \tau_{ij}}{\partial x_j} \\
\frac{\partial \overline{\mathbf{u}_i}}{\partial x_i} &= 0
\end{align*}
\]

(1)

(2)

where \( x_i \ (i = 1, 2, 3) \) are the coordinates, as replaced later by \( (x, y, z) \), \( \overline{\mathbf{u}}_i \) are the corresponding filtered velocity components and \( \overline{p} \) is the filtered pressure. The subgrid-scale (SGS) stress tensor \( \tau_{ij} \), defined by

\[
\tau_{ij} = \overline{\mathbf{u}_i \mathbf{u}_j} - \overline{\mathbf{u}_i} \overline{\mathbf{u}_j}
\]

(3)

is modeled using the model by Germano et al. [9], together with the least-square method suggested by Lilly [10].

A finite-volume method based on integration over the control volume was used to solve the model equations (1) and (2). The bounded central difference scheme was used for spatial discretization.
discretizations, and the second-order three-level implicit scheme was used for time advancement. The SIMPLEC method was used for the pressure-velocity coupling.

\[ U(r)/U_c = (1-2r/D_0)^{1/7} \]

where \( U_c \) is the centerline velocity and \( U(r) \) is the streamwise component of time-averaged velocity at radial distance, \( r = (y^2+z^2)^{1/2} \), from the centerline of the pipe. At the pipe-inlet and the triangular orifice the bulk mean velocities \( U_i = 4.8 \text{m/s} \) and \( U_1 = 33.3 \text{m/s} \), respectively. In most experimental set-ups, there are background disturbances present in the jet produced. In the present study, we constructed the background disturbance such that its frequency spectrum consists of the Kolmogorov spectrum [11]. The background disturbance was set to be (r.m.s. value) of the background disturbance was set to be 0.01.

\[ U_j = 0.1 \text{~m/s} \]  
\[ U_c = 33.3 \text{~m/s} \]

The results show that the frequency content of the disturbance is higher than the background disturbances present in the jet produced. In the present study, we constructed the background disturbance such that its frequency spectrum consists of the Kolmogorov spectrum [11]. The background disturbance was set to be (r.m.s. value) of the background disturbance was set to be 0.01.

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chamber flow may be characterized as the central forward flow and outer low-speed backward flow which occupies most of the inner space at $x/D \leq 1.25$. Perhaps noteworthy, some low-speed forward flow exists in a small space near the inner wall at $x/D \leq 0.5$.

To verify the present simulation by experiment, we plot in Figs. 5(a-b) the inverse centerline velocity decay ($U_c/U_1$) and streamwise variation of the half-velocity widths ($y_{1/2}, z_{1/2}$) together with previous PIV measurements of England et al. [8] in the similar OTJ flows outside the chamber. Here $U_c$ denotes the centerline mean velocity, while the half-velocity widths $y_{1/2}$ and $z_{1/2}$ represent the lateral locations at which the mean velocity is $U = 0.5U_c$. As demonstrated, the LES results agree reasonably well with those of England et al. [8] measured over the range $2.9 < x/D < 5.1$. Fig. 5(a) shows that $U_c$ decreases monotonically in the chamber ($x/D < 2.5$), then increases at $x/D < 3$ immediately downstream of the chamber exit, and decreases again farther downstream at $x/D > 3$. The increase over the near-field region $2.5 < x/D < 3$ can be explained here. At the exit plane of the chamber, a circular lip of diameter $d_l = 0.82D$ is placed with a backward-facing $45^\circ$ ramp. The asymmetric jet emerging from the chamber therefore would be deflected at $45^\circ$ by the lip so that it passes across the nozzle axis in the near-field (centred at $0.5D$ downstream of the exit or $x/D = 3$) almost all the time, resulting in the centerline mean velocity being relatively higher at $x/D < 3$.

Fig. 5(b) shows the half-velocity widths ($y_{1/2}, z_{1/2}$) of the OTJ in the central $xy$ and $xz$ planes. These widths were calculated from $y$-direction and $z$-direction across the entire jet at several $x/D$ values and at each location the average values of $y_{1/2}$ and $z_{1/2}$ on either side of the jet centerline are accounted. As expected, both $y_{1/2}$ and $z_{1/2}$ increase monotonically with downstream distance. However, the growth of $y_{1/2}$ is faster than that of $z_{1/2}$ for $x/D > 5$. This is likely because the oscillating triangular jet has preferred azimuthal directions at the three corners, e.g., one in the $xy$ plane, as observed by Lee et al. [7]. Note that the jet flow precesses (i.e. rotates azimuthally) about the chamber axis in a continuously unstable manner.

Fig. 6: Typical instantaneous OTJ flow structure inside the chamber. Part (a): 3-D views of streamlines; part (b): projections of streamlines and longitudinal velocity contours in the $yz$ planes located at different $x/D$ indicated.

**Characteristics of the instantaneous OTJ flow**

The typical instantaneous OTJ flow structure inside the chamber is illustrated by three-dimensional (3-D) streamlines in Fig. 6 and also by the longitudinal projections of streamlines in Fig. 7. It is demonstrated clearly that the jet issuing from the triangular exit suddenly expands into the chamber, re-attaches the inner wall and oscillates roughly gyroscopically about the chamber axis due to some natural instabilities. Notably, three streamwise vortices are initially formed in conjunction with the exit triangle sides, interacting with each other and also with the central main jet. Simultaneously a quantity of ambient fluid is induced into the chamber from the outside and goes upstream together with the reverse fluid from the jet itself, forming a secondary flow rotating around in the opposite sense to the oscillation. These flow characteristics are qualitatively consistent with experiments by deduction [6]. Unfortunately, however, the latter cannot display any similar 3-D pictures inside a chamber due to the complexity of the OTJ flow and also the constraint of those optical measurement technologies.
In order to obtain the average oscillation frequency precisely, the frequency spectra of the fluctuating velocity at \( x/D = 2.49, y/D = \pm 0.42 \) and \( z/D = 0 \) is shown in Fig. 8. The pressure spectrum measured by England et al. [8] at \( x/D = 2.49, y/D = 0.42 \) and \( z/D = 0 \) is also included for comparison. Obviously, all the spectra exhibit a broad peak. If we choose the frequency at which the spectrum is the highest as the dominant oscillation frequency \( f_p \), the present LES data show that \( f_p \approx 24 \text{ Hz} \). This value of the frequency agrees well with that obtained by England et al. with the peak count method but is higher than that determined from their spectrum. The corresponding Strouhal number defined by

\[
St \equiv \frac{f_p d_j}{U_j}
\]

is approximately 0.0054. This value is about two orders of magnitude lower than that of acoustically forced flow from a circular duct (0.15 \( \leq St \leq 0.6 \)) [16] and a triangular duct (\( St \approx 0.3 \) and 0.51) [17].

Conclusion

In the present study, we have simulated using LES the oscillating triangular jet (OTJ) produced through a specific chamber described in Fig. 1 and Section 2. Calculations of the mean OTJ flow at \( Re_t = 17,900 \) are well verified by recent measurements of England et al. [8]. The simulated OTJ flow displays several interesting aspects that are summerised below:

1. After discharging downstream into the chamber, the jet reattaches the inner wall and oscillates about the chamber axis only roughly in a gyroscopic fashion.

2. The axis-switching phenomenon, often occurring in non-circular free jets [14], also takes place in this partially-confined and oscillating triangular jet.

3. Three strong longitudinal vortices arise along with the jet in the initial region at \( x/D \leq 1 \). These three vortices appear to merge as a larger one or disappear near the location where the unmixed core region is ended. The swirling intensity is expected to increase upstream and achieves the maximum near the chamber upstream end.

4. Due to the jet entrainment inside the chamber, some external fluid is induced into the chamber and joins the reverse fluid from the jet to form a secondary swirling flow, which occupies most of the chamber.

5. The in-chamber flow may be overall characterized to be the central forward OTJ flow and the outer backward swirling stream which occupies most of the inner space at \( x/D \leq 1.25 \).

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Reference


