Oscillatory phenomena of a turbulent plane jet flowing inside a rectangular cavity

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Abstract

In this study, the oscillation of a turbulent plane jet flowing inside a rectangular cavity is investigated under some conditions of the location of the exit of the jet in the cavity. The experimental study is made essentially by hot wire anemometer and supplemented by visualizations. The numerical study is based on two statistical models of the turbulence: the mono-scale energy - dissipation (k - ε) and the two-scales energy - flux_models. Three types of flow regimes have been observed for different positions of the jet inside the cavity: no-oscillation regime, stable-oscillation regime and unstable-oscillation regime. The structural properties of the flow and the frequency of the flapping of the jet of the stable-oscillation flow regime have been detailed experimentally and numerically in different situations: the location of the exit of the jet in the cavity and the Reynolds number.

1 Introduction

The practical interest of such a phenomenon is related to the various problems in industrial applications such as:

1 - mixing of fluids
2 - combustion
3 - cooling or heating by forced convection
4 - air conditioning
5 - renewal of fluid inside a cavity
flowmeters with no moving solid parts. Some studies [1] Shakouchi & al. [2], Shakouchi, [3], Maurel [4] and Villermaux & Hopfinger [5] of the self sustained oscillation of a jet inside a cavity have been made and its flow characteristics are considerably made clear. The jet-cavity interaction is investigated for a great number of location of the jet exit in the cavity. Three types of flow regimes are observed: no-oscillatory, stable-oscillatory and unstable-oscillation.

2 Experimental apparatus and procedure

The experimental device consists mainly of a rectangular cavity in which a rectangular duct can be displaced horizontally and vertically. The nozzle is adapted to produce two-dimensional jet flow with low turbulence level (figure 1).

The velocity measurements are carried out using constant temperature hot wire anemometry. The measuring device is composed of a Dantec multi channel (56C00) apparatus including a signal analysis components. A single hot wire probe are made of a 5 µm diameter platinum-plated tungsten wire is used. These probes have been calibrated using a calibration system before and after each experimental session. A memory oscilloscope is used for sampling and recording one or two signals during a small time interval.
Flow visualisations

A CFT Taylor smoke generator is used for visualisations of the flows structures. This generator produces a white smoke composed of very small droplets of vegetable oil mixed in compressed carbon dioxide. The smoke is injected upstream at the inlet of the channel in order to obtain a nice homogeneous white flow at the jet exit. The flow is lightened by a projector located at the bottom end of the cavity through a vertical transparent slot in the mid plane. Motion photographs series have been shot with a camera using a frequency of 2 pictures per second.

3 Numerical modelling

3.1 Single scale \( k - \varepsilon \) model

The two equations’ model Schiestel [6] and [7] is based on the concept of Prandtl-Kolmogorov’s turbulent viscosity. The turbulent Reynolds stress tensor is obtained by an algebraic relation:

\[
\frac{2}{3} \delta_{ij} k - \overline{u_i u_j} = \nu_t \left[ \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right]
\]

(1)

where

\[
\nu_t = C_\mu \frac{k^{3/2}}{\varepsilon}
\]

(2)

The closing is then obtained by calculating the equations of \( k \) and \( \varepsilon \):

\[
\frac{dk}{dt} = \nabla \cdot \left[ \nu_t \left( \frac{\nabla}{\sigma_k} + \frac{\sigma_k}{\sigma_{k,t}} \frac{\partial k}{\partial x_k} \right) + \nu_t \left[ \frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} \right] \frac{\partial U_i}{\partial x_k} - \varepsilon \right]
\]

(3)

\[
\frac{d\varepsilon}{dt} = \nabla \cdot \left[ \nu_t \left( \frac{\nabla}{\sigma_{\varepsilon}} + \frac{\sigma_{\varepsilon}}{\sigma_{\varepsilon,t}} \frac{\partial k}{\partial x_k} \right) + C_{el} \frac{\varepsilon}{k} \nu_t \left[ \frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} \right] \frac{\partial U_i}{\partial x_k} - C_{e2} \frac{\varepsilon^2}{k} \right]
\]

(4)

where

\[ C_\mu = 0.09 ; \quad C_{el} = 1.44 ; \quad C_{e2} = 1.92 ; \quad \sigma_{k,L} = 1.0 ; \quad \sigma_{k,t} = 1.0 ; \quad \sigma_{\varepsilon,L} = 1.0 ; \quad \sigma_{\varepsilon,t} = 1.3. \]

3.2 Two scales energy-flux model

The schema adopted in the present work consists in subdividing the average spectrum in three zones (figure 3) Schiestel [6] and [7]:
The partial kinetic energies and the spectral flows are determined from the next transport equations:

\[
\begin{align*}
\frac{d k_P}{dt} &= P - \varepsilon_p + \text{Diff}(k_p) \\
\frac{d k_t}{dt} &= \varepsilon_p - \varepsilon_t + \text{Diff}(k_t)
\end{align*}
\]

(5) (6)

\[
\varepsilon = \varepsilon_t
\]

(7)

\[
\frac{d \varepsilon_p}{dt} = C_{1p} \frac{\varepsilon_p}{k_p} P - C_{2p} \frac{\varepsilon_p^2}{k_p} + \text{Diff}(\varepsilon_p)
\]

(8)

\[
\frac{d \varepsilon_t}{dt} = C_{1t} \frac{\varepsilon_t \varepsilon_p}{k_t} - C_{2t} \frac{\varepsilon_t^2}{k_t} + \text{Diff}(\varepsilon_t)
\]

(9)

where \( C_{1p} \), \( C_{2p} \), \( C_{1t} \) and \( C_{2t} \) may be functions of the spectrum’s form defined by \( \xi = k_p / k_t \), knowing that \( k = k_p + k_t \) and \( \nu_t = \frac{C_P k^2}{\varepsilon_p} \).

In first approximation we will attribute constant numerical values to these coefficients. The linking conditions are satisfied for the value \( \xi = 3 \) of the spectrum’s form ratio. The corresponding values in this case are:

\[
C_{1p} = 1.65 \quad C_{2p} = 1.92 \quad C_{1t} = 1.75 \quad C_{2t} = 1.82
\]

The presence of a rigid wall and the condition of adherence result in an increase of viscous effects and a decrease of the intensity’s levels of the turbulence. This
will necessitate a special treatment for the region next to the wall. In this work, we have used the method of wall functions Launder & al. [8].

4 Numerical procedure

The considering flow is fully turbulent and instationary. It concerns a fluid with constant physical properties. The equations for the mean and the turbulent variables can be written by the following general form:

$$\rho \frac{\partial \Phi}{\partial t} + \rho \frac{\partial}{\partial x_j} \left( \rho U_i \Phi \right) = \frac{\partial}{\partial x_j} \left[ \Gamma_\Phi \frac{\partial \Phi}{\partial x_j} \right] + S_\Phi$$

(10)

where $\Gamma_\Phi$ and $S_\Phi$ are determined for each variable from the global equations of the movement. The two-dimensional discrete form of this equation is:

$$A_p \Phi_p = A_E \Phi_E + A_W \Phi_W + A_N \Phi_N + A_S \Phi_S + b$$

(11)

where $\Phi_p$, $\Phi_E$, $\Phi_W$, $\Phi_N$ and $\Phi_S$ are the variable’s values of $\Phi$ at $P$, $E$, $W$, $N$ and $S$ respectively (figure 3) Patankar [9] and Jones & al. [10], while the $A_i$ ($i = P$, $E$, $W$, $N$ and $S$) and $b$ proceed from the eqn (10).

The velocity’s components are quantified at shifted nodes and the velocity-pressure coupling is realized with the algorithm SIMPLE. The source term has to be linearized for the stability of the solution. The three-diagonal structure of the coefficients of the associated matrix to the eqn (11) requires the utilization of the algorithm TDMA which includes a Gaussian process followed by an inverse substitution.

![Figure 3: cell of integration](image)

The examined flow presents a considerable variation of the direction of velocity vector especially at the region of the bottom of the cavity. We have then proceeded to the application of the algorithm TDMA along the two
directions South-North and East-West. This double sweeping is intended to increase the stability of the convergence.

5 Results

5.1 Geometrical and dynamical parameters

Geometrical parameters are specified on figure 4. Dimensionless quantities have been built on these geometrical parameters:

\[ X = \frac{X_1}{X_0}, \quad H = \frac{H_1}{H_0} \tag{12} \]

The location of the point of measurement (M on figure 4) is defined by its dimensionless coordinates:

\[ x = \frac{(X_1 - x_1)}{X_1}, \quad h = \frac{h_1}{H_0} \tag{13} \]

The dynamical parameter is the Reynolds number based on the mean velocity at the jet exit and the height of the nozzle and where \( v \) is the kinematic viscosity:

\[ Re = \frac{U_0 h_0}{\nu} \tag{14} \]

The frequency of oscillation in the unsteady case is characterised by a Strouhal number defined on the same quantities \( U_0 \) and \( h_0 \) and where \( f \) is the frequency of oscillations:

\[ St = \frac{f h_0}{U_0} \tag{15} \]

![Figure 4: Geometrical parameters](image)

5.2 Identification of the flow regime's zones

The nature of the interaction is determined numerically and experimentally by the time analysis of the mean velocity for every point of the cavity. These points are obtained by sweeping in the two directions \( x \) and \( h \) the whole cavity, the jet exit being successively located on each node of a rectangular mesh. We
detected three types of flow regimes. This distinct zones named I (no oscillation), II (unstable oscillation) and III (stable oscillation) are summarized one the figure 5. This diagram is valid for Reynolds number varying from 1000 to 5000. This diagram is symmetrical toward the mid transverse plane of the cavity because gravity effect is negligible.

![Diagram of the several flow regime zone's](image)

**Figure 5: - Diagram of the several flow regime zone's**

### 5.3 Time analysis of oscillations

The oscillation of the jet have been evidenced experimentally and numerically by the periodicity of the mean velocity (figure 6). The two-scales model and the experience velocity signals are practically similar. The numerical calculations using the k-ε model and the two-scales model both predict an oscillatory regime. The measured filtered velocity signal shows a periodic pattern with a main peak and several secondary peaks that are also clearly visible on the calculated signal at the same point in the cavity x=0.3, X=0.8, H=0.5, Re=4000, h=0.300. The experimental period in time is found to be T=1.84 s and the calculated values of the period for the same case are very close, with T=1.87s for the single scale model and T=1.81s for the two-scales model. For the numerical prediction the periodic variations is observed for the mean and the turbulent variables such as velocity modulus (U), transverse velocity component (V), mean pressure (P), turbulent kinetic energy (k) etc......

The figure 7 shows the calculated Fourier transforms of these velocity at the same locations by the two-scales model. The fundamental frequency is clearly determined by the first peak in the Fourier modes A/U₀ distribution. The two models give similar results, but the two-scales model produces more energetic harmonics that are noticeable on the time signals of the velocity modulus.
a) Photograph of the signal of the velocity modulus as function of time

b) Calculated based on single scale model

c) Calculated signal based on two-scales model

Figure 6: Variation of the velocity modulus as function of time by different methods (x=0.3, X=0.8, H=0.5, Re=4000, h=0.300)
Another phenomenon have been shown in this study is the existence of a phase shift between the pressure and the mean velocity in the oscillating jet. This phase shift proves the existence of a feedback mechanism with time lag effects Ayukawa & Shakouchi [11]. We can see this phenomenon on figure 8 for one calculated point. For this case, the phase shift between the transverse component of mean velocity and the mean pressure is evidenced by the numerical prediction based on the two-scales model. The pressure oscillation is somewhat ahead in advance phase before the velocity signal. The mechanisms of oscillation in confined jets are linked to feedback effects of perturbations but seem to have several origins depending on the particular geometry considered. In the case of a jet flowing in an enlarged channel the perturbations are convected upstream by the recirculating flow and amplified by the instability of the jet, while in the case of impinging jets pressure effects are important in the feedback mechanisms Villermaux & Hopfinger [5].

The frequency of the flapping of the jet between the two laterals wall of the cavity varies linearly as the Reynolds number and the location of the jet in the cavity (H and X). On figure 9 the Strouhal number based on jet exit conditions is represented versus the Reynolds number. The Strouhal number is found practically constant over the domain of Reynolds numbers considered. The experimental results are finely reproduced by the two models, with a slightly better agreement for the two-scales model. This result also means that the frequency varies linearly with the Reynolds number. This result has been also obtained by many authors in similar flow geometries [1] to [5].

Figure 7: Fourier modes of the mean velocity time signal, two scales prediction for (x=0.3, X=0.8, H=0.5, Re=4000, h=0.300)
Figure 8: Phase shifts between the pressure and the transverse velocity signals at x=0.6, h=0.50, X=5, H=0.5, Re=4000

Figure 9: Variation of Strouhal number as Reynolds number at H=0.5

5.4 Mean structure of the oscillatory flow

The figure 10 illustrates photographs of the flapping motion of the jet oscillating during one period of time (T). The analysis of these photos and numerical prediction lead to the description of the mechanism of one oscillation. Two counter-rotating eddies are clear on each side of the jet inside the cavity at each time. When the jet is deflected from its mean position, the two lateral eddies start moving; the largest eddy from the unattached side go upstream and produces a
pressure defect; when it approaches the lateral exit, the fluid is sucked (figure 4) in the inside of the cavity at the opposite side; this new flow rate entering the cavity increases, the corresponding eddy goes downstream and then forces the jet to be deflected to the opposite side where a pressure maximum is then created and the mechanism is periodically reproduced [2].

![Image](image-url)

Figure 10: Experimental flow visualization of six stages of one period of time of oscillation (Re=4000, X=0.8 and H=0.425).

### 6 Conclusion

We have presented an experimental and numerical study of a turbulent plane jet confined in a rectangular cavity. For certain geometrical configurations and for sufficiently large Reynolds numbers, this system exhibits self-sustained oscillations characterized by well-defined frequency of the jet. The flow patterns are classified into three classes, namely stable oscillation, unstable oscillation, and no oscillation flows depending the location of the jet in the cavity. Dimensional analysis predicts that the frequency is in proportion to the Reynolds number when the Strouhal number is constant. Two distinguishable moving eddies on both sides of the jet are evidenced experimentally by visualization. Oscillatory flows studied in the literature using two-equations models like the flow behind the square cylinders (Jones and Launder model [10]) do not produce unsteadiness, to capture of unsteadiness behind cylinder necessitate modifications [12,13,14]. In this present work, the oscillations are predicted satisfactory by two-equations models because the mechanism of oscillation of the jet is due to pressure effects. The use of multiple scale turbulence model allowed to improve the numerical predictions compared to the standard k-ε model.
References


