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Control of self-sustained jet oscillations in 3D thin rectangular cavity

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ABSTRACT

The aim of this work is the control of an oscillatory jet submerged in a 3D thin rectangular cavity, with two opposite injections added on its thinnest sidewalls at the same height, perpendicular and above the jet exit. This type of control is required when the characteristics of the main jet (Reynolds number, nozzle size) are not modifiable. Due to Coanda effect, the oscillations of the main jet occur in the widest plane of the cavity, and depend on the mass flow of two injections. Unsteady, 3D problem is solved by finite volume method using URANS modeling. The validation confirms that second order models predict more accurately this flow configuration than first order models. Two behaviors of time average of flow fields corresponding for two ranges of β are detected. When $0 \leq \beta < 25.51\%$, the main jet effect decreases to reach the case without lateral injections ($\beta = 0$). Similarly for $25.51 \leq \beta \leq 50.67\%$, the main jet effect diminishes for higher value of β. Thus, $\beta = 25.51\%$ is a threshold value for this type of flow configuration. Moreover, for $\beta = 25.51\%$ the minimum values for the kinetic energy, main jet deflection angle and oscillations frequency are reached. Furthermore, the deflection angle reaches its maximum value for $\beta = 12.90\%$ and the best deflections are recommended for $\beta < 25.51\%$.

1. Introduction

Confined jets inside rectangular cavities were performed by several researchers since the last century for their interesting practical applications. Under some conditions, self-sustained oscillations are generated by Coanda effect (Bourque and Newman (1960); Kirshner and Katz (1975)) which may always be a source of deterioration of equipments in some engineering applications. Rockwell (1983) and Rockwell and Naudascher (1978), have explained that self-sustained oscillations occur when a shear layer is bounded by two recirculation zones in confined geometries. Lawson and Davidson (2000), Mataoui and Schiestel (2009) have also found that these oscillations occur in thin cavity by Coanda effect (Kirshner and Katz, 1975). However, this phenomenon is not yet absolutely understood. Some studies have been performed for better metal quality required in industrial equipment (Chaudhary et al., 2009; Gebert et al., 1998; Molloy and Taylor, 1969).

However, these types of configuration may require passive or active control. Passive control requires no additional fluid injection or external forces; it is generally based on the geometric parameters and Reynolds number of the jet. Many studies have been developed for this type of control, which particularly have deepened the phenomenon of self-sustained oscillations by modifying the geometrical parameters of the cavity and Reynolds number (Toshihiko, 1981; Maurel et al., 1996; Lawson et al., 2005; Mataoui and Schiestel, 2009; Denisikhina et al., 2005; Bouchet, 1996; Ogab, 1985; Mataoui et al., 2003; Mataoui et al., 2001; Iachachene et al., 2015). In addition, the oscillating jets submerged in a thin cavity were studied by several researchers (Honeyands and Molloy, 1995; Kalter et al., 2014a; Pacheu et al., 2000; Lee et al., 2015; Righolt et al., 2015). Recently, many researchers have developed different methods of active control are performed by the addition of a further flow or external forces (Smith et al., 1997; Seifert and Pack, 1999; Pack and Seifert, 1999; Miller et al., 1999; Kalter et al., 2014b). The thrust vectoring of an oscillatory jet in a thin rectangular cavity

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Nomenclature

Latin symbols

b	Cavity thickness (m)
d_1	Main jet pipe diameter (m)
d_2	Lateral jet pipe diameter (m)
f	Frequency of the main jet (Hz)
H	Lateral injection sidewall jet location (m)
L	Cavity length (m)
P	Pressure component (Pa)
$\rho\overline{uu}$, $\rho\overline{vv}$, $\rho\overline{ww}$	Perpendicular Reynolds stresses (m^2/s^2)
Re	Reynolds number (–)
s	Submerged depth of main jet nozzle (m)
U_2	Lateral jet injection velocity (m/s)
U, V, W	Velocity components (m/s)
V_1	Main jet velocity (m/s)
W	Cavity width (m)
Y_R	Sidewall main jet attachment position (m)

Greek Symbols

α	Deflection angle (°)
β	Mass flow rates ratio (–)
ν	Kinematic viscosity (m^2/s)
ρ	Density (Kg/m^3)

is ensured by only one lateral injection perpendicular to the main jet, was performed numerically and experimentally by Lawson et al. (2005). Depending on the flow rate and location of the injection, they have found that the oscillations may be suppressed, generating a stationary interaction, and they have determined the maximum deflection angle which induces the best active control. This work is devoted to the control of the self-sustained oscillations of a confined jet in a cavity, by the addition of two symmetrical lateral jets, perpendiculars to the main jet, placed in the thinner cavity sides, at the best location recommended by Lawson et al. (2005). This type of control may be required in several engineering applications having uncontrollable velocity of main jet; opposite and perpendicular injections are necessary to adjust the amplitude and frequency of oscillations. In this study, the two lateral injections were arranged at the position recommended by Lawson et al. (2005) which induces the best deflection of the jet in the case of a single injection (Fig. 1). It should be noted that the addition of the second injection in the opposite wall, maintains the oscillatory flow. The main objective of this study is to investigate the influence of the two side jets on the main jet behavior by analyzing average and instantaneous flow fields (the oscillation frequency and the angle of deviation of jet) for several mass flow ratios.

2. Methodology

2.1. Governing equations

All calculations are performed by means of 3D-URANS turbulence modeling. The fluid considered is water and it is assumed incompressible with constant physical properties. The time averaged equations are represented by means of conservation principles of time averaged mass (Eq. (1)) and momentum (Eq. (2)) equations:

$$\frac{\partial U_j}{\partial x_j} = 0 \tag{1}$$

$$\rho\left(\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\frac{\partial U_i}{\partial x_j} - \rho\overline{u_i u_j}\right] \tag{2}$$

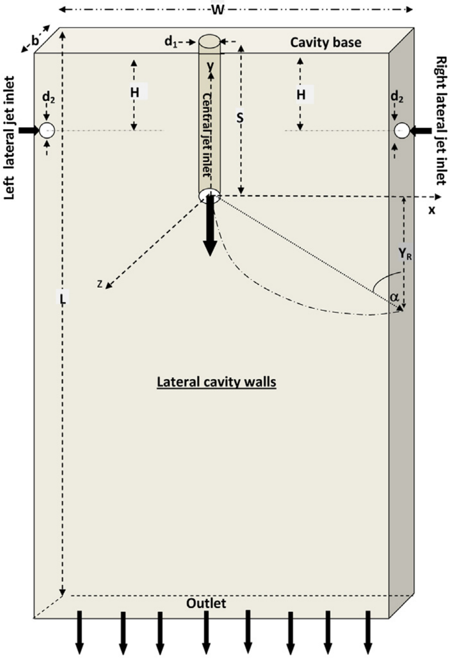

Fig. 1 – Sketch of the experimental setup and computational domain.

The capital symbols correspond to the averaged variables, while lowercase symbols represent the corresponding fluctuations. In order to model the turbulent shear stresses $\rho\overline{u_i u_j}$, three turbulence models are tested: standard k–ε, Shear Stress Transport k–ω and Reynolds stress model. The standard k–ε model (Jones and Launder, 1972) is based on the concept of turbulent viscosity of Prandtl–Kolmogorov, which correctly predicted the flows at high Reynolds numbers. The second turbulence two-equation model is the SST k–ω model Menter (1993) and Wilcox (1988), which uses a formulation k–ω in region of the boundary layer and k–ε model outside the boundary layer. To combine these two models, the standard k–ε model has been transformed in k–ω equations, which leads to introduction of a cross-diffusion term in the dissipation rate equation. All first order models, Reynolds stresses components are deduced from Boussinesq equation as follows:

$$\rho\overline{u_i u_j} = \frac{2}{3}\rho k\delta_{ij} - \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

Reynolds stress model (RSM) (Launder et al., 1975) is used for second order turbulence closure. It is constructed on transport equations for all components of Reynolds stress tensor and dissipation rate ε.

2.2. Numerical procedure

The numerical prediction is performed by finite volume method by means of CFD code ANSYS-Fluent. This numerical method (Patankar, 1980) requires a conservative form for all equations in terms of convection, diffusion and source (Eq. (4)):

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_j}\left(\rho U_i\phi - \Gamma_\phi\frac{\partial\phi}{\partial x_j}\right) = S_\phi \tag{4}$$

The spatial discretization is achieved on collocated meshes. The SIMPLE algorithm is used for pressure–velocity