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Precessing vortex core in a swirling wake with heat release

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ABSTRACT

Numerical simulation of the non-stationary three-dimensional swirling flow is presented for an open tube with a paraxial heat source. In the considered type of swirling flows, it is shown that a precessing vortex core (PVC) appears. The obtained PVC is a left-handed co-rotated bending single-vortex structure. The influence of the heat release enhancement on parameters of PVC is investigated. Using various turbulence models (the Spalart–Allmaras, k–ω and SST models), it is shown that an increase in the heat-source power leads to an increase in the PVC frequency and to a decrease in the amplitude of PVC oscillations. Moreover, we conduct the linear stability analysis of the simplified flow model with paraxial heating (the Rankine vortex with the piecewise axial flow and density) and demonstrate that its results correspond to the results of numerical simulations rather well. In particular, we prove that the left-handed bending mode ($m = +1$) is the most unstable one in the low-density wake and its frequency increases with a decrease of density ratio that is similar to the behavior of precession frequency with an increase of heat-source power.

1. Introduction

Swirling flows are known to be very significant for devices with heat release such as swirl combustion systems (Gupta et al., 1984; Syred, 2006), aero-engines (Hassa et al., 2002), plasma dynamic systems (Klimov et al., 2008, 2009, 2011), hydrogen plasma generators (Jasinski et al., 2008), etc. At sufficient swirl numbers, the central recirculation zone (CRZ) is generated. The precessing vortex core (PVC) arises at the boundary of the direct and the counter flows (Syred, 2006; Fernandes et al., 2006; Alekseenko et al., 2007; Shtork et al., 2008; Huang and Yang, 2009; Vigueras-Zuñiga et al., 2012, etc.). In practice it may lead to the desired effect being achieved. Otherwise, the consequences can be catastrophic. On the one hand, this precessing motion can enhance mixing and has a positive effect on the combustion. It can improve the heat release efficiency and reduce NO_x emissions (Froud et al., 1995; Wong et al., 2004). On the other hand, the strong pressure and velocity oscillations generated by the PVC can be resonant to the thermo-acoustical vibrations of a vortex chamber (Syred, 2006; Duwig and Fuchs, 2007). Thus, this phenomenon is potentially dangerous and must be taken into account for the design of powerful facilities, in particular hydro and gas turbines, vortex combustors, and plasma chambers.

The common features of the PVC obtained from experimental investigations and numerical simulations are as follows.

Firstly, the PVC is an unsteady 3D-motion, which is observed as a time-dependent asymmetrical flow pattern with the vortex center precession in an azimuthal plane around the geometrical center. Usually, this precession coincides with the basic swirling flow. While Dellenback et al. (1988) has presented the experimental evidence of vortex precession in a direction opposite to the swirl direction for low swirl numbers without the CRZ.

Secondly, the PVC has helical structure and is formed by the unstable bending flow modes $m = \pm 1$. The formation of either the positive (left-handed) bending mode, which winds in the opposite direction to the basic flow rotation, or the negative (right-handed) bending mode, which winds in the direction of the basic flow rotation, depends on a number of factors including the swirl ratio and the expansion ratio (Dellenback et al., 1988; Guo et al., 2001, 2002, etc.). Based on the experimental results, the positive first helical mode $m = +1$ of instability arising as a result of vortex breakdown (Benjamin, 1962) is identified by Gupta et al. (1984), Lucca-Negro et al. (2001), Syred (2006), Duwig and Fuchs (2007), Shtork et al. (2008), etc. in the wakes. The direct numerical simulation of a three-dimensional vortex breakdown in swirling flow shows that a transition to helical breakdown modes is caused by a

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sufficiently large pocket of absolute instability in the wake of the bubble, giving rise to a self-excited global mode (Ruith et al., 2003). Two distinct eigenfunctions corresponding to azimuthal wavenumbers $n = -1$ and $n = -2$ have been found to yield a left-handed helical or double-helical breakdown mode, respectively. In Ruith et al. (2003), the minus sign represents the fact that the winding sense of the spiral is opposite to that of the flow, i.e. $n = -m$. These results are confirmed by the stability analysis and experimental investigations of the three-dimensional coherent structure (co-rotating but counter-winding helical structure with $m = +1$) in a swirling jet undergoing vortex breakdown (Liang and Maxworthy, 2005; Gallaire and Chomaz, 2006; Oberleithner et al., 2011; Alekseenko et al., 2013).

Thirdly, the precession frequency is obtained experimentally as dominant frequency of static pressure or velocity oscillations (Fernandes et al., 2006; Shtork et al., 2008; Oberleithner et al. 2011). It normally grows linearly with the mass flow rate regardless of swirl devices (Gupta et al., 1984) and changes non-monotonically with the swirl ratio S (Guo et al., 2001, 2002; Fernandes et al., 2006; Shtork et al., 2008).

The majority of investigations of PVC in non-isothermal swirling flows are the experimental observations of this phenomenon in combustion or electric discharge chambers.

According to Syred and Beer (1972), Schneider et al. (2005), Roux et al. (2005), Syred (2006), and Vigueras-Zuñiga et al. (2012), the amplitude of PVC decreases strongly in reactive combustion flows. The PVC can become intermittent, double and irregular (Vigueras-Zuñiga et al., 2012; Valera-Medina et al., 2013). In the other configuration of the combustion chamber (Duwig and Fuchs, 2007), the PVC is not suppressed and, moreover, the PVC induces a nontrivial flame dynamics. Available data concerning the PVC frequencies in combustion systems have been assembled in the review of Syred (2006). For the PVC with the 100% axial fuel entry, there is a tendency to an increase of PVC frequency with the equivalence ratio until the formation of double helical PVC structures.

The other series of experiments studying the non-isothermal swirling flow structure are connected with firing of different discharges, applied to various practical tasks of plasma aerodynamics, plasma assisted ignition and combustion control (Klimov et al., 2008, 2009, 2011; Zavershinskii et al., 2009, 2011, 2013). Features experimentally observed in the formation of glowing zones of the direct current (DC) discharge at various mass flow rates have been analyzed and qualitatively explained. Conditions obtained experimentally for the onset of transitions between corona and pinch types of one electrode radio frequency (RF) capacitive discharges in the swirl airflow at atmospheric pressure have also been considered in detail (Zavershinskii et al., 2009, 2011, 2013). Explanations were based on the numerical simulations of turbulent swirling flows with local heat sources. In particular, we have obtained the bifurcation map of mass flow rates across tangential and axial swirler inlets for three different regimes (without CRZ, transient case with short CRZ, full tube length CRZ) in the experimental geometry (Zavershinskii et al., 2011) (an example of such map is presented in Section 2.3). It coincides sufficiently with the experimentally observed boundaries of discharge structure bifurcations (Moralev, 2010). We have shown that the observed growth of the long pinch is directly connected with the extensive CRZ and the thermal wave propagation (Zavershinskii et al., 2011). The helical structure of this pinch is connected with the PVC formation (Zavershinskii et al., 2013).

Although some experimental and theoretical results are available, the basic understanding of the influence of heat release on parameters of the PVC remains incomplete. According to Vigueras-Zuñiga et al. (2012), the precessing vortex core (PVC) is a well-known coherent structure which development, intensity and occurrence have not been well documented. We will study this problem in a rather simplified approach of the swirling flow created in the open tube described by Klimov et al. (2009) and Moralev (2010) with a paraxial source of heat without the specification of its nature.

In the present work, we have thoroughly studied the influence of the heat release enhancement on parameters of the PVC. The paper is organized as follows. In Section 2.1, the governing equations are presented in forms which allow us to make the numerical simulation of the non-stationary 3D turbulent swirling flow. In Section 2.2, the results of the numerical simulations of the PVC in the open tube with a paraxial source are obtained and discussed. In Section 3, the numerically obtained non-stationary helical structure is compared to the predictions of the linear stability analysis. For this purpose, we get and numerically solve the dispersion equation for linear disturbances using the simple model of the swirling wake with the counterflow and the light core. As a result, we come to the conclusion that both methods give the same type of the most unstable bending structure and qualitatively similar trends of behavior of the frequency of oscillations generated by the PVC in dependence on the heat source power. Finally, Section 4 summarizes the main results.

2. Mathematical modeling

2.1. Geometrical configurations, governing equations and boundary conditions

The swirler and tube geometry is sketched in Fig. 1. The swirler has four tangential inlets and an axial inlet with the independent gas supply. Another end of the tube is open.

For modeling turbulent flow in this tube, we use the unsteady Reynolds averaged Navier–Stokes (URANS) equations which can be written in the form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_i)}{\partial x_i} = 0,$$

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial\left(\rho v_i v_j\right)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial v_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_i}\left[-\rho\overline{v'_i v'_j}\right]$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial[v_i(\rho E + P)]}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\kappa + \frac{c_P \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} + v_i\left(\tau_{ij}\right)_{eff}\right] + \Im(\vec{x}),\ E = h - \frac{P}{\rho} + \frac{v^2}{2},\ P = \frac{\rho \mathrm{T}}{\mathrm{M}}, \quad (1)$$

where

$$\left(\tau_{ij}\right)_{eff} = \mu_{eff}\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j}\right) - \frac{2}{3}\mu_{eff}\frac{\partial v_k}{\partial x_k}\delta_{ij}$$

is the deviatoric stress tensor, $[-\rho\overline{v'_j v'_j}]$ are Reynolds stresses which must be modeled in order to close the set of equations, v_i, v'_j, ρ, T, P, E, and h are the main and fluctuating velocity components, density, temperature, pressure, total energy, and enthalpy, respectively; $\Im$ is the energy source, μ, μ_t, μ_{eff} are the molecular, turbulent, and effective viscosity coefficients, respectively; c_p is the molar specific heat capacity at constant pressure; κ is the thermal conductivity coefficient; Pr_t is the turbulent Prandtl number.

We imposed the no-slip and fixed temperature conditions along the tube walls and the fixed mass flow conditions at the tube inlets.

The inlet turbulent intensity is set to zero basing on the experimental data. In experimental setup (Moralev, 2010; Klimov et al., 2011), the honeycombs that consist of a set of thin close-packed quartz tubes with inner diameters less than 3 mm are located at