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Experimental analysis of the swirling flow in a model rectangular gas turbine combustor

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ABSTRACT

A 2D PIV technique was applied to investigate the swirling flow motion inside a rectangular-shaped model chamber. Flow velocity profiles are analyzed through several planes at the center and off-axis of the swirler over three cross-sectional views of x–y, y–z, and x–z. A comparison of axial and radial velocity profiles is given over these planes to ascertain the effect of rectangular confinement inside the combustor. Flow kinetic energy near the walls is investigated to study the highly disturbed regions and areas of flow impingement. A vorticity and vector analysis is presented on the x–z plane where the flow development was found to be under the effect of a CCW and CW swirler alongside the imbalanced condiment ratio.

1. Introduction

With rising interest in NO_x reduction within the mid to late 1960s, swirl stabilizers were used in gas turbine engines. Since then, higher combustion efficiency and lower emissions have remained the primary interests of gas turbine engine developers. The necessity of burning the entire fuel, avoiding pressure drops and maintaining a uniform temperature has led to the promotion of a flame stabilization shelter where the fuel is continuously ignited and complete combustion is provided. To impose such a feature, swirlers with a variety of designs were modified to regulate fluid velocity to provide a complete combustion of fuel. Swirling flows naturally represent themselves as spiraling motion dominated by azimuthal and axial components of velocity, massive shear stress and high turbulence intensity within flow layers [1]. The degree of swirl is usually characterized by *Swirl Number S*, which is a non-dimensional number representing the axial flux of the swirl momentum divided by the axial flux of the axial momentum multiplied by the equivalent nozzle radius [2]. The toroidal shape of recirculated flow is widely known as the central toroidal recirculation zone (CTRZ), which stabilizes the flow and provides a suitable environment for a proper mixing ratio and reduced NO_x generation [3].

As the swirl number increases, the radial spread of the jet also increases until a certain value ($S > 0.6$) where the axial adverse pressure gradient exceeds the forward kinetic forces and makes the flow reverse back to the swirler. Yet a very large swirl induces instabilities inside the combustion chamber, resulting in an unstable vortex core. This phenomena appears as a precessing motion of the vortex core within the axial flow direction known as (PVC), and the boundaries of PVC were found located somewhere between the zero velocity and the zero streamline, resulting in an increase in the degree turbulence intensity and deriving undesirable features such as thermo-acoustic instabilities [4,5]. To this extent, understanding its behavior and predicting its modes has become vital and of great interest. Studies [6–8] have shown that the swirling flow in a confined configuration is strongly affected by wall friction and the development of a corner recirculation zone (CRZ). Additionally, the length of the CTRZ was found to be in close relation to the geometry of the chamber. Research showed that the confinement effects would be more conspicuous where the confinement ratio [9] – the ratio of the cross-sectional area of the test chamber to the exit area of the swirler- is less than 0.9 for high swirl numbers [10]. A study on the different confinement levels indicated the existence of a diverse number of recirculation zones for larger and smaller ducts [11]. However, there is still a lack of studies addressing flow behavior in confined configurations in comparison to other key features of swirling flow.

Swirlers could be characterized in several ways, but an important one is based on the number of flow passages. There can be

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Nomenclature

°C	centigrade
CCD camera	a camera whose imaging system uses three separate charge-coupled devices (CCDs)
CCW	Counter Clockwise
CRZ	corner recirculation zone
CTRZ	central toroidal recirculation zone
CW	clockwise
D	diameter, mm
k	turbulent kinetic energy, m^2/s^2
$\dot{m}$	mass flow rate, kg/s
NO$_x$	a generic term for the mono-nitrogen oxides NO and NO$_2$
PIV	Particle Image Velocimetry
PVC	Precessing Vortex Core
S	swirl number, dimensionless
stokes number (stk)	a dimensionless number characterizing the behavior of particles suspended in a fluid flow
TARS	triple annular swirler
u	axial velocity component, m/s
v	radial velocity component, m/s

Subscripts

hub	swirler's hub
i	inner
o	outer
rms	root mean square
sw	swirler
x	at the flow direction

Greek symbols

ω	vorticity
∂	partial derivative sign

single, *dual annual*, or *triple annular swirlers* (*TARS*), which can be configured as counter or co-rotating swirlers. A comparison between dual-counter and co-rotating swirlers in confined configurations concluded a larger size of CTRZ in the counter-rotating swirler, while the corner recirculation zones exhibited roughly the same amount of mass flow [12]. Furthermore, a faster decay of turbulence and stronger positive axial pressure gradient were also observed for these swirlers [13]. Reacting flow investigation showed a relatively wider flame for the counter-swirl flame, while the co-swirl configuration contributed to a shorter flame length and a better fluid mixing ratio, resulting in lower NO$_x$ production [14–16]. Thus, counter-rotating swirlers were proven prior to the co-rotating ones.

Here, a dual-axial counter-rotating swirler in a rectangular model of a gas turbine combustor is studied experimentally. The purpose of this paper is to present a detailed analysis of swirling flows within certain confined configurations. To this extent, a 2D PIV experiment was conducted, and velocity profiles were depicted in diverse planes. Measurement planes were placed on three X–Y and three X–Z planes that were set within the radial distances of 0 and ±3.0 in the Z and Y directions. Further, turbulent kinetic energy was studied on two planes at radial distances of $Y/D = \pm 8.7$ very close to the chamber boundaries. It is believed that the analysis of these planes would come in handy to comprehend the flow development structure confronting non-square or circular confinements. The results of this paper are meant to be a comprehensive depiction of the confined swirling flows with a rectangular chamber.

2. Experimental setup

The velocity components were measure by a 2D Particle Image Velocimetry (PIV) system. The system consisted of a double pulse Nd:YAG Laser (maximum energy of 120 mJ/pulse, 15-Hz pulse rate), a CCD camera (PowerViewTM Plus 2 MP resolution of 1.6 K × 1.2 K pixels and a speed of 32 frames/s) a synchronizer system and a dynamic range intensity of 12 bit. The laser sheet thickness was 1.5 mm, and a cylindrical lens was used as a luminosity source. The water was seeded by polyamide seeding particles with a mean diameter of 20 μm and relaxation time of 0.23 × 10–4. Particles density and dynamic viscosity is 1.03 × 103 kg/m^3 and 1.002 × 10–3 Pa s respectively. In the state that the maximal local velocity reaches 10 m/s, the typical length scale is 4.1 × 10–3 m. The resulting Stokes number is 0.056, and thus velocity errors due to particle slip are considered negligible. The percentage of particle mass from total water mass was found to be 0.00231%, larger than 0.00038% to eliminate the seeding mass quantity effect [17].

It is known that the 2D PIV technique may draw unrealistic results while dealing with highly 3D flows such as swirling motion [18]. In such cases, the laser sheet is not aligned with the velocity vector with maximum magnitude since the flow is highly 3D dimensional. This error occurs when the particle moves perpendicular to the laser sheet thus the projected velocity vector is neglected and may affects the final measured velocity data [19]. In particular when it comes to experiments with air as working fluid, due to high dissipation rate providing reasonable data from horizontal section may not be feasible. However, different techniques were developed to remedy such flaws [20] suggesting that great care should be taken defining various PIV setting such as tracking particles, interrogation size, and laser pulses. A brief review on the draw backs and error analysis of PIV systems is given in [18]. In addition to this, error correction schemes such as 50% overlapping method [21] are used widely and remarkably reduces the out-of-plane motion effects on the flow field. In the presented experiment and comparing to the previous air works, the coherent structures formed by water and its higher viscosity resulted in a monotone exchange of momentum within the flow layers from the swirler exit till the outlet. As a consequence, the magnitude of velocity and velocity gradients within vertical and horizontal sections are at similar levels.

Under these circumstances, it is acceptable to consider the possible errors due to the strong out-of-plane motion of same order since the maximum velocity components are comparable within vertical and horizontal sections. The theoretical velocity at the swirler exit was estimated to be 1.8 m/s, suggesting the approximate time of 834 μs for a particle to pass the laser sheet thickness. Thus, the time interval between the laser pulses was set to 150 μs, short enough to keep a single seeding particle inside the laser sheet to avoid any out-of-plane motion effects. Velocity fields were evaluated from particle images using a PIV software (Insight 4G TSI) applying a FFT cross-correlation method on a Nyquist grid considering a 50% overlap with a final interrogation window size of 32 × 32 pixels. The magnification factor is 7.8 pixels/mm for both x and y direction. Mean flow maps were gathered averaging 100 instantaneous vector fields. The uncertainty given from the PIV software Insight 4G was reported less than ±4.0%.