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Swirling dual-disk double-concentric jets at low annulus Reynolds numbers

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HIGHLIGHTS

- Swirling double-concentric jets were modulated by dual-disc.
- Flow fields and mixing characteristics were experimentally investigated.
- Three characteristic flow modes are identified.
- Large turbulent intensities occurred near wake region.
- Mixing capability is significantly improved.

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ABSTRACT

The flow characteristics and mixing properties of swirling dual-disk double-concentric jets at low annulus Reynolds numbers were studied. The flow patterns, velocity characteristics, and mixing properties were characterized using the laser-assisted smoke flow visualization method, particle image velocimetry (PIV), and tracer-gas concentration detection technique. Three characteristic flow modes,*annular jet-dominated wake*, *central jet-dominated wake*, and *central jet-dominated radial flow*, were observed within different ranges of central jet Reynolds numbers for the annulus Reynolds and the swirl numbers were less than 270 and 0.245. The flow structure of the *central jet-dominated wake* (a dual-ring recirculation zone in the wake region and two pairs of counter-rotating vortices in the gap between the up- and downstream disks) allowed the annular jet fluids to be transported into the gap between the upstream and downstream disks to premix with the central jet fluids before further being transported to the disk wake. The flow fluctuation intensities in the wake of the *central jet-dominated wake* were significantly larger than those of the *annular jet-dominated wake* and *central jet-dominated radial flow* because the large-scale fluctuation eddies that possess large turbulence kinetic energy existed in the wake. These properties prominently promoted the mixing in the *central jet-dominated wake*.

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1. Introduction

The swirling jets and bluff-body wakes have been used in many industrial applications because installing a bluff body in a flow or imparting swirling motion to a flow can generate a recirculation bubble in the wake region, thereby enhancing the flow mixing and combustion efficiencies. Either the swirling jets with high degrees of swirl motion or the large blockage ratio of non-swirling bluff body can produce a recirculation zone with high turbulence fluctuations in the near field [1–7]. This vortical wake structure plays an important role in mixing capability, spreading rate, and flame stabilization [8–12]. In many practical devices, such as gas turbines, furnaces, boilers, cyclone separators, and combustors, the values of swirl and Reynolds numbers higher than about 0.6 and 18,000, respectively, are required to induce a reverse flow zone near the jets exit [4].

In some applications, the combined effects of swirling motion and bluff body help to enhance the turbulence intensities near the jets exit region. Escudier and Keller [13] report on a swirling flow issued from a nozzle with a circular cylinder located concentrically inside the nozzle. The blockage ratios were 0.25 and 0.39. When the swirl strength reached a critical value, an axisymmetric

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Nomenclature

A_a	Area at exit of swirling jet, $[=\pi\ (D_o^2 - D^2)/4]$, 550 mm^2
A_c	Area at exit of central jet, $(=\pi\ d^2/4)$, 19.6 mm^2
B	Blockage ratio at exit of annular swirling jet, $(=D^2/D_o^2)$, 0.563
C_{CO_2}	Concentration of carbon dioxide gas, %
$C_{CO_2,s}^{max}$	Maximum concentration of carbon dioxide in single-disk case, %
$C_{CO_2,d}^{max}$	Maximum concentration of carbon dioxide in dual-disk case, %
D	Diameter of upstream disk, 30 mm
d	Diameter of central jet at exit, 5 mm
D_c	Diameter of downstream disk, 14 mm
D_h	Hydraulic diameter of annular swirling jet at exit, $(=D_o - D)$, 10 mm
D_m	Mean diameter for calculating swirl numbers, $[=(D + D_o)/2]$, 35 mm
D_o	Outer diameter of annular swirling jet at exit, 40 mm
H	Distance from upstream disk to downstream disk, 10 mm
$l_{L,u}$	Lagrangian integral length scale of u'
$l_{L,v}$	Lagrangian integral length scale of v'
Q_a	Volumetric flow rate of annular flow
Q_c	Volumetric flow rate of central jet
Re_a	Reynolds number of annular flow, $(=u_a D_h/\upsilon)$
Re_c	Reynolds number of central jet, $(=u_c d/\upsilon)$
$R_{\tau,u}$	Autocorrelation coefficient of u'
r	Radial coordinate, originated from center of circular disk
S	Swirl number of annular jet
u	Instantaneous axial velocity component
$\overline{u}$	Time-averaged axial velocity
u'	Root-mean-square of axial velocity fluctuations
u_a	Mean axial velocity of annular swirling jet at exit, $(=Q_a/A_a)$
u_c	Mean axial velocity of central jet at exit, $(=Q_c/A_c)$
v	Instantaneous radial velocity component
$\overline{v}$	Time-averaged radial velocity
v'	Root-mean-square of radial velocity fluctuations
$\overline{u'v'}$	Shear stress per unit density of velocity fluctuations
w	Azimuthal velocity component
x	Axial coordinate, originated from center of upstream disk
η	Mixing improvement index, $\left[= (C_{CO_2,s}^{max} - C_{CO_2,d}^{max})/C_{CO_2,s}^{max}\right]$
τ	Shifting time in calculating correlation coefficient
$\tau_{L,u}$	Lagrangian integral time scale of u'
$\tau_{L,v}$	Lagrangian integral time scale v'
υ	Kinematic viscosity of air

recirculation bubble was observed immediately downstream the of center cylinder. Sheen et al. [14] investigated several characteristic flow modes by studying the effects of swirling flow on the wake behind a cylindrical tube with a blockage ratio of 0.23. The effects of the swirling strength and blockage ratio on the flow characteristics were carried out by Huang and Tsai [15]. The results indicated that when the blockage ratio is higher than about 0.1, the recirculation zone near the jet can form even at low annulus Reynolds numbers.

By using the smoke-wire flow visualization technique and laser Doppler velocimetry, Huang and Tsai [16] presented the flow structures and turbulence properties of swirling double-concentric jets with a large blockage ratio of 0.563. A jet was issued from a circular hole of 5 mm in diameter located at the center of the circular disk. They found that at the large blockage ratio, the recirculation zone can form at swirl and Reynolds numbers lower than those recommended by Gupta et al. [4]. Several flow modes, such as single bubble, dual rings, vortex breakdown, and vortex shedding, were observed. The disadvantage of the double-concentric jets with a large blockage ratio was that at high central jet Reynolds numbers, the turbulence intensities near the field were low, and therefore, induced a low mixing efficiency.

Huang and Yen [17] used a circular disk located downstream of the blockage disk to enhance the mixing efficiency of swirling double-concentric jets. They found that, at a fixed annulus Reynolds number of 218 and a corresponding swirl number of 0.194, the flow behavior of the swirling vortical wake can be modulated and formed into several characteristic modes (e.g., bubble escape, bubble encapsulation, and gap flow). They concluded that when the downstream disk was located at a proper distance above the blockage disk, the axial momentum of central jet flow transferred radially induced an increase of axial and radial turbulence properties; therefore, the mixing capability was improved.

This study presents the effects of central jet Reynolds numbers on the flow and mixing characteristics of swirling dual-disk double-concentric jets at low swirling annulus Reynolds numbers. The results indicated that the recirculation zone near field can be formed even at low swirling annulus Reynolds number ($150 < Re_a < 270$, $0.135 < S < 0.254$). The instantaneous flow pattern was carried out by using the smoke-wire technique. Velocity vectors, streamlines, turbulent intensities, and time and length scales of fluctuations were resolved by PIV measurement. The tracer-gas concentration distributions were examined to better understand the mixing characteristics of flow modulated by dual-disk configuration. The results of this study are possible to use in industrial applications such as industrial burners, fluid mixers, cyclone separators, non-premixed bluff-body combustors, and propulsion apparatuses.

2. Experimental methods

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. The swirling airflow provided by the ring blower went through an acoustic filter, a pressure regulator, a needle valve, a rotameter, and then directly fed into a cylindrical test rig. The test rig consisted of a plenum chamber, honeycomb, mesh screens, settling chamber, and a swirl generator. The swirl generator had 12 guide vanes arranged in a pitch circle with a radius of 175 mm. The NACA 0012 wing section was selected as the vane profile and was installed at a 70° deflection angle. The azimuthal velocity component was imparted to the annular flow via the axisymmetric array of guide vanes. A contoured nozzle, with a contraction ratio of 9.0 and a diameter (D_o) of 40 mm, was attached to the cylindrical test rig to accelerate the annular flow. A circular disk, which was denoted as the upstream disk, with a blockage ratio (B) of 0.563, was placed concentrically at the exit of the nozzle to create a bluff-body wake. Another circular disk, which was denoted as the downstream disk, with a diameter (D_c) of 14 mm and a thickness of 1 mm, was placed horizontally at a distance (H) of 10 mm ($0.33D$) downstream of the upstream disk. The downstream disk was supported by 2 thin rods with a diameter of 0.45 mm. The central jet was supplied by either compressed air or carbon dioxide via a small nozzle assembly to perform flow visualization or tracer-gas concentration measurement, respectively. The flow went through four layers of mesh screens installed in the nozzle assembly to reduce turbulence fluctuations. The nozzle had a fifth-order polynomial profile with

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