

FLOW AND SPREADING BEHAVIORS OF COAXIAL JETS WAKE

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Abstract - Flow and spreading behaviors of swirling jets using a dual-blockage disk are studied experimentally. The control and blockage disks are placed concentrically in tandem. The smoke flow patterns are obtained using the flow visualization technique. The axial velocity and turbulence intensity are detected using a 1-D hot-wire sensor. The jet spreading characteristics are illustrated by using an Edge Detection Method. Two pairs of lung-formed vortices and triangle-formed vortices are induced in downstream wake at $Rec \leq 200$. Two vortices are found near the field at $200 < Rec < 700$, while no toroidal structure was found above the reflected jet at $Rec \geq 700$. The recirculation bubble length was increased with increasing Rec until $Rec < 700$. The axial velocity and turbulence intensity at $200 < Rec < 700$ are significantly greater than those in other modes. At $Rec \geq 700$, the shear-layer vortices are found far away from the control disk.

Key words - Flow visualization; Swirling flow; Bluff-body wake; Double-concentric jets; Spreading jet

1. Introduction

Many engineering applications use double-concentric jets as a traditional method to enhance mixing and combustion efficiencies, such as burners, incinerators, gas turbine combustors, and cyclone separators. The prominent feature of the two concentrically jets is a recirculation zone induced in the near jet exit [1-2]. This recirculation bubble has occurred as the outer jet passes through a bluff body located at near jet exit. Inside this recirculation bubble, the turbulent fluctuations exhibited high values; therefore, the mixing and combustion efficiencies can be improved. In addition, another concentrically jet is usually injected into the wake of jets to increase the mixing capabilities of the coaxial jets. The mixing between the two jets is processed fast and efficiently by operating the central jet velocities at low values. In contrast, a high central jet momentum can penetrate the toroidal zone near the wake and make less diffusion of the central flow into the annular flow. Therefore, mixing and combustion efficiency decreased moderately. Generally, large blockage ratios and large Reynolds numbers are needed to create a large reversed flow region or a toroidal vortex in the downstream wake.

Swirling jet across a bluff body was reported as another conventional method to promote a better mixing and combustion process in broadly practical uses. Similar to that represented in the coaxial jets, the recirculation zone could be formed near the wake to take advance of the high-turbulent region. In many industrial applications, in order to induce the reverse flow region near jet, the swirl (S) and the Reynolds (Re) numbers are required to operate at higher than 0.6 and 1,800, respectively [3]. Some investigators studied combining advantages of the bluff-body wake and swirling jet for the purpose of improving the mixing efficiencies [4-6]. For instance, Huang and Tsai [4] combined the swirling flow and bluff body effects for

the double-concentric jets. Several complex flow structures inside the recirculation zone were identified by varying the central jet Reynolds numbers. Typically, at a large value of central jet velocity, the turbulence intensities inside the recirculation zone were low because the central jet passed through the bubble and combined with the swirling flow, then went directly to the downstream wake. Obviously, at this stage of the flow condition, there was not much diffusion of the central jet flow into the toroidal vortices in the swirling wake. Hence, the mixing index could not be able to attain an expectation of adding the swirling motion into the double-concentric jets.

This study proposes a control method using a dual-control disk located in the downstream wake of the coaxial jets to overcome the disadvantages of the swirling jets. The influences of the central jet flow on the flow fields and spreading behaviors of the swirling wakes as using two control disks were investigated experimentally. The flow patterns were obtained by using a traditional smoke flow visualization technique. The velocities and turbulence intensities were measured and reported by a 1-D hot-wire anemometer sensor. The results drawn from this fundamental study can be considered for small scale combustion applications (e.g., burners) in order to improve the mixing and combustion process.

2. Methods

2.1. Apparatus

The experiments were performed at the Thermal Science and Fluid Mechanics Laboratory, NTUST, Taiwan. The experimental configuration of this study was shown in Figure 1. Before entering into a cylindrical chamber, the inlet airflow was supplied from a ring blower, went through a regulator, needle valves, and a rotameter. The apparatus consists of a plenum chamber, honeycombs, a settling chamber, and a swirler. 12-guided vanes (i.e., a swirl generator) were installed to impart the swirl motion into the annular flow. To accelerate the flow, a nozzle ($CR = 9.0$) was attached at the exit of the chamber. The nozzle exit has a diameter of 40 mm. The swirling jet flow was evolved from the slot between the nozzle assembly and the blockage disk. The blockage disk ($D = 30$ mm) was mounted at the jets exit. The central jet was provided by a compressed air tank using a nozzle with a length and a CR of 300 mm and 900, respectively. The control disk ($D_c = 14$ mm) was installed at $H = 0.33D$ [7]. The thickness of blockage and control disks was 1 mm. Two thin rods (0.45 mm diameter) were used to maintain the parallelism between the disks. The control disk was installed to study the spreading jet in combining the effect

with the annular swirling jet. The nozzle assembly was installed concentrically with the blockage disk and the control disk. The flow rates of the swirling jet and central jet were measured by using rotameters which were calibrated by an opened-loop low-speed wind tunnel. A cylindrical coordinate was set at the center of the blockage disk in the exit plane. The swirling intensity was denoted by the swirl number (S). It was indicated as the ratio of the axial flux of angular momentum to the axial flux of axial momentum. The swirl number was defined by Gupta et al. [3], as shown in Eq. (1):

$$S = \int_{\frac{D}{2}}^{\frac{D_0}{2}} uwr^2 dr / \frac{D_m}{2} \int_{\frac{D}{2}}^{\frac{D_0}{2}} u^2 r dr \quad (1)$$

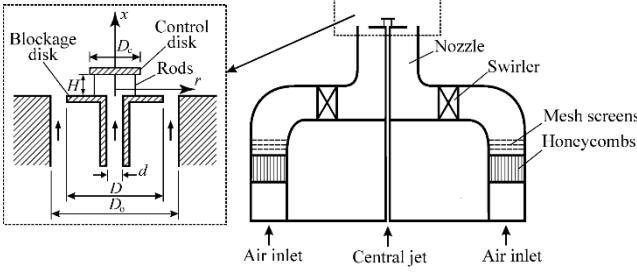


Figure 1. Experimental setup

2.2. Flow Visualization

Regarding Mie scattering method [8] as using an assisted laser, the smoke-patterns flow visualization technique was performed to reveal the flow behaviors in the wake of the swirling coaxial jets. For the smoke images, a wire (made by tungsten which has a diameter of $100 \mu\text{m}$) placed at the axial level of $x/D = 0.03$ was used for illustrating smoke flow patterns. A DC power was connected to the smoke wire, which was brush-coated by the mineral oil and used to generate fine smoke streaks. For the time-average images, the central jet was driven into a homemade smoke generator before it released out with a high-density smoke. A green continuous laser with a power, a wavelength, and a laser-sheet thickness of 3.3 W, 532 nm, and 0.5 mm, respectively, was used to illuminate the seeding of smoke in the symmetry plane of swirling wake. The instantaneous flow images were recorded in a high resolution using a CCD camera (model: IDT Y4).

For the purpose of determining the jet spreading of swirling coaxial jets, a still camera (model: Nikon D3200) was used to observe the long-exposure images. The jet spread width (W/D) estimated from the long-exposure images was used to indicate the radial length of the recirculation bubble. To examine the boundary of the jet spreading, the edge detection method was used. Before applying this method, the long-exposure images were smoothed to reduce the noise from the background. The gray-level images were selected by numerical values (ranged from 0 to 255) which presented the light intensity at each pixel. The radial positions where the gray-level values shift immediately from zero to greater than zero were roughly defined as the jet boundary.

2.3. Velocity Estimations

A 1-D hot-wire anemometer (H-WA) was used to detect the velocity data. A platinum wire with a diameter

and a length of 5 mm and 1.5 mm, respectively, was used to replace the original H-WA probe tungsten wire. The response frequency of the H-WA was maintained at 20 kHz. A 3-D mechanism (i.e., XYZ table) was used to obtain the measuring locations. The H-WA was calibrated by using a Pitot tube and a pressure sensor. The axial velocity and its fluctuation were estimated along the central axis and several axial distances. To measure and control the output, signals of the H-WA, a DAQ system was required.

3. Results and Discussion

3.1. Instantaneous Smoke Flow Images

The instantaneous smoke flow patterns of the swirling coaxial jets in a symmetrical plane modulated by a control disk are shown in Figure 2. The annular flow conditions were $Re_a = 230$ and $S = 0.207$, while Re_c is varied to reveal the flow features and jet spreading ($Re_c < 1000$) of the swirling coaxial jets.

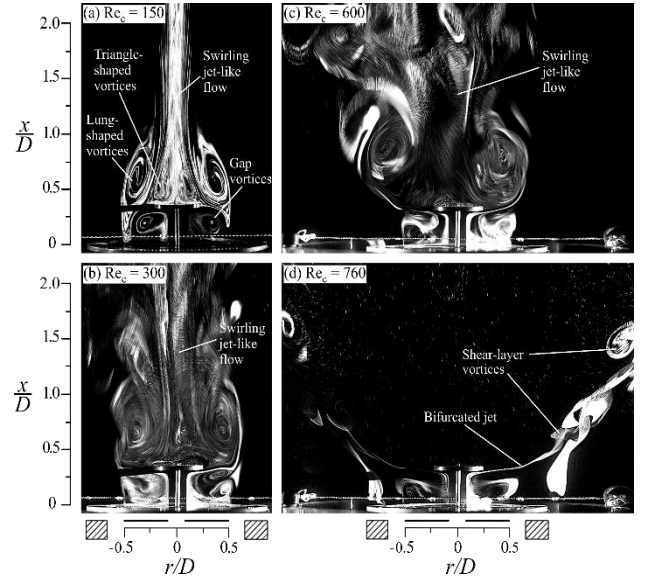


Figure 2. Instantaneous smoke flow patterns.
 $Re_a = 230, S = 0.207$

At $Re_c \leq 200$, as shown in Figure 2(a), e.g., at $Re_c = 150$, the central jet fluid releases from the top of the blockage disk, impinges the control disk and deflects radially. Two rotating vortices exist in the gap between the blockage disk and the control disk due to the air entrainment effects. A pair of triangle-formed vortices evolves downstream the control disk. A pair of lung-formed vortices is evolved from the edges of the blockage disk and fully covers the triangle-formed vortices due to the Coanda effect. This is because the effect of air entrainment is stronger than that of the annular jet flow as it separated from the edges of the blockage disk. A swirling jet-like flow evolves and rotates vertically in downstream of the control disk and moves to the downstream wake. The pair of lung-formed vortices encapsulates all the gap vortices, triangle-formed vortices, and swirling jet-like flow.

At $200 < Re_c < 700$, as shown in Figure 2(b) and (c) at $Re_c = 300$ and $Re_c = 600$, respectively, two pairs of

rotating vortices (i.e., gap vortices) are formed in between the two controlled disks. The central jet fluids impinge the control disk, separated radially from the edges of the control disk, and then turn upward. A pair of counter-rotating vortices is evolved from the bottom edges of the control disk due to the Coanda effect. At this stage of Re_c , a swirling-jet like flow is still found in downstream of the control disk. The smoke flow patterns in Figure 2(b) and (c) become more turbulence than those in Figure 2(a). However, the size of the outer counter-rotating vortices exhibited in Figure 2(b) and (c) is much larger than those of the lung-formed vortices shown in Figure 2(a). In other words, the recirculation bubble length of the outer counter-rotating vortices increases with increasing the central jet Reynolds number (Re_c). Consequently, this remarkable development would promote the good sign of enhancing the mixing processes.

At $Re_c \geq 700$, as shown in Figure 2(d), e.g., $Re_c = 760$, the central jet fluids with a very large momentum impinge the control disk, bifurcate outward, and shoot radially far away from the control disk. The outer recirculation bubble and swirling jet-like flow shown in Figure 2(a-c) are no longer displayed in Figure 2(d). This could be explained that the central jet fluid totally dominates the flows and its bifurcated jet effect is stronger than that of the annular flow. Two rotating vortices between the blockage and control disks are still distinguished. In the downstream of the control disk, some smoke particles induced by the bifurcated jet exhibit a random motion with very low speed due to the Coanda effect.

At a far distance from the control disk (within the image window), the shear-layer vortices characterized by the bifurcated jet are identified. This type of Kármán vortex-shedding vortices [9] appeared above the bifurcated lines since the radial distance of about $r/D > 0.6$. The analyzed videos recording confirmed that the shedding frequency of shear-layer vortices increases as increasing the Re_c . In other words, the shear layers that are formed from both the inner and outer edges of the swirling annular jet inhibited this interaction.

3.2. Spreading Characteristics

Figure 3 exhibits the time-averaged smoke flow images in the conditions of different central jet Reynolds numbers (i.e., $Re_c = 150, 300$, and 600). The recirculation bubble is formed near the wake at $x/D \leq 1.5$. The detailed structures of flow in the recirculation bubble are smeared by the long exposure setting. The smoke particles are seeded from the smoke generator via the central jet.

Figure 3(a-c) show that the central jet flow is blocked by the control disk, bent radially, carried and trained by the gapping, outer, and inner vortices, then passed through the central swirling jet-like flow into the downstream region. The radial length of the recirculation bubble increases when increasing Re_c . This phenomenon can be confirmed by using the Edge Detection Method for $Re_c < 700$. For instance, as shown in Figure 4, the normalized jet spread width (W/D) estimated by the abrupt gray-level change at $x/D = 0.5$ was about 1.53, 1.72, and 2.8 at $Re_c = 150, 300$, and 600 , respectively. In other words, the

jet spread width (W/D) was increased by increasing the central jet fluids momentum.

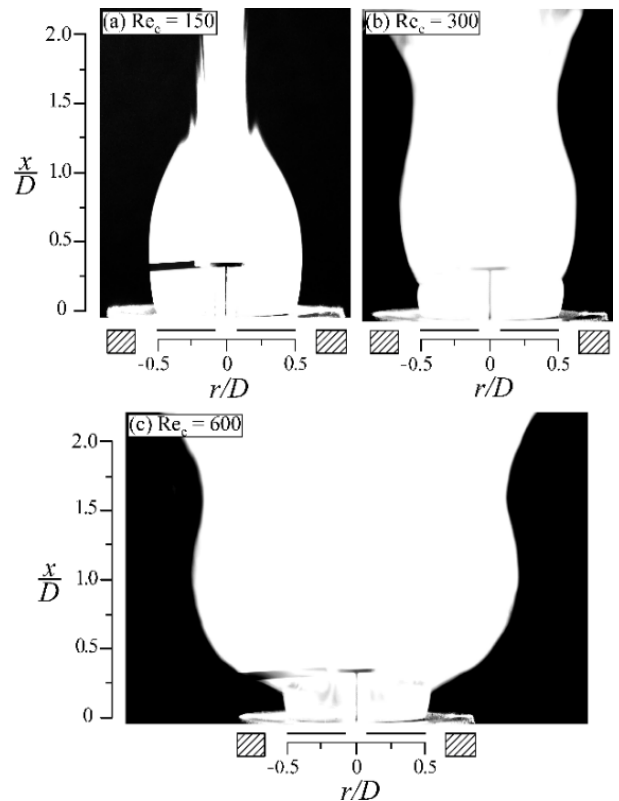


Figure 3. Long-exposure smoke flow patterns.

$Re_a = 230, S = 0.207$

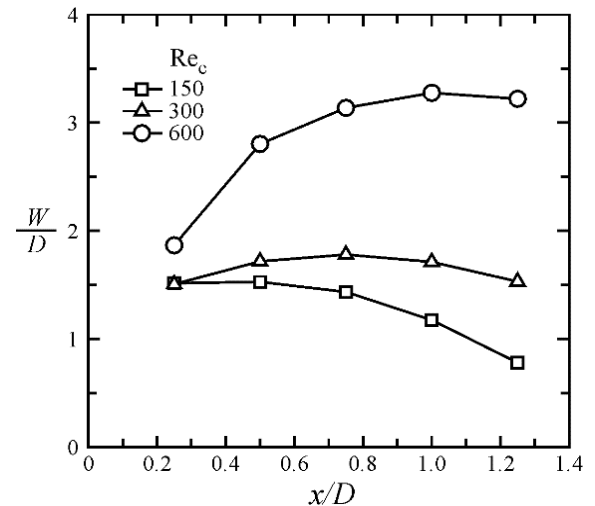


Figure 4. Normalized jet spread width. $Re_a = 230, S = 0.207$

In Figure 4, at the axial distance of $x/D < 1.2$, the jet spread width (W/D) decreases gradually when the axial distance increases at a low Reynolds number (e.g., $Re_c = 150$), while at a high Reynolds number (e.g., $Re_c = 600$), it increases rapidly by increasing the axial distance. This can be explained as the diffusion and dispersion induced by mass transport processes are greater than those induced in the swirling single-disk coaxial jets [4]. In other words, in the case without the control disk, the central jet fluids move directly downstream without forming the toroidal vortices.

At $200 < Re_c < 700$, the large recirculation bubble

promotes large turbulent intensity downstream of the blockage disk; therefore, the mass transfers from the central jet into the annular jet could be increased when the central jet fluids velocity increases. Thus, the mixing process of the swirling double-concentric jet might be improved.

At $Re_c \geq 700$, the time-averaged smoke flow features could not be obtained similarity to those shown in Figure 3(a-c) because there is no smoke flow pattern was found downstream of the control disk as shown in Figure 2(d).

3.3. Velocity Characteristics

Figure 5 presents the normalized axial velocities ($\bar{u}/u_a$) and axial turbulence intensities (u'/u_a) distributions along the central axis at $Re_c = 150, 300$, and 760 . The axial velocities and turbulence intensities are normalized by u_a .

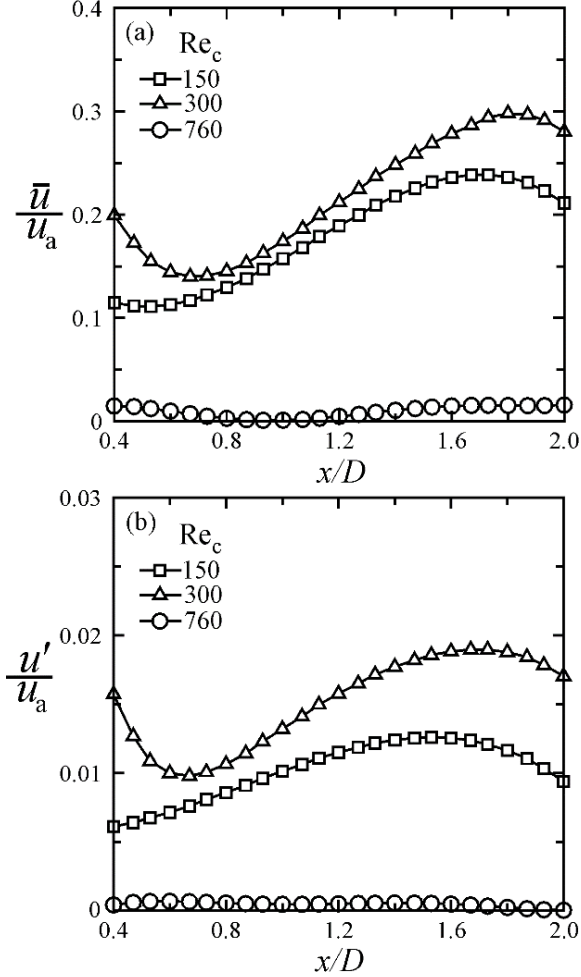


Figure 5. Axial velocity distribution along centerline.
 $Re_a = 230, S = 0.207$

In general, the axial velocity and turbulence intensity at $Re_c = 150$ and 300 are obviously larger than those at $Re_c = 760$. In Figure 5(a), at low central jet Reynolds (e.g., $Re_c = 150$), the axial velocity ($\bar{u}/u_a$) decreases slightly as the axial distance increases at $x/D < 0.5$. This is because of the triangle-formed vortices is induced near the control disk regime (Figure 2(a)). At $0.5 \leq x/D \leq 1.7$, $\bar{u}/u_a$ accelerates dramatically with increasing the axial level because the swirling jet-like flow dominated the downstream wake. At $x/D > 1.7$, $\bar{u}/u_a$ decreases when increasing x/D .

At $Re_c = 300$, within the recirculation bubble displayed in Figure 2(b), the axial velocity decreases drastically as increasing the axial level until $x/D \leq 0.7$. $\bar{u}/u_a$ increases rapidly at $x/D \leq 1.8$, then decreases moderately at $x/D > 1.8$ due to the influences of the converging-diverging of the swirling jet-like flow.

At a large central Reynolds number (e.g., $Re_c = 760$), the values of $\bar{u}/u_a$ are significantly lower than those at $Re_c = 150$ and 300 along the centerline in the downstream wake. In Figure 5(b), the same scenario that happened in axial velocities, the turbulence intensities (u'/u_a) at $Re_c = 300$ exhibit larger values than those at $Re_c = 150$ and 760 . This is because of the large reverse flow induced in the downstream of the control disk. That would promote a better mixing capability for the swirling double-concentric jets. At $Re_c < 700$, the larger the central jet Reynolds numbers are, the greater the turbulence intensities are. When the $Re_c > 700$, the value of u'/u_a exhibits a significantly low value of about zero. This is because the reverse flow structures did not appear in the wake as shown in Figure 2(d).

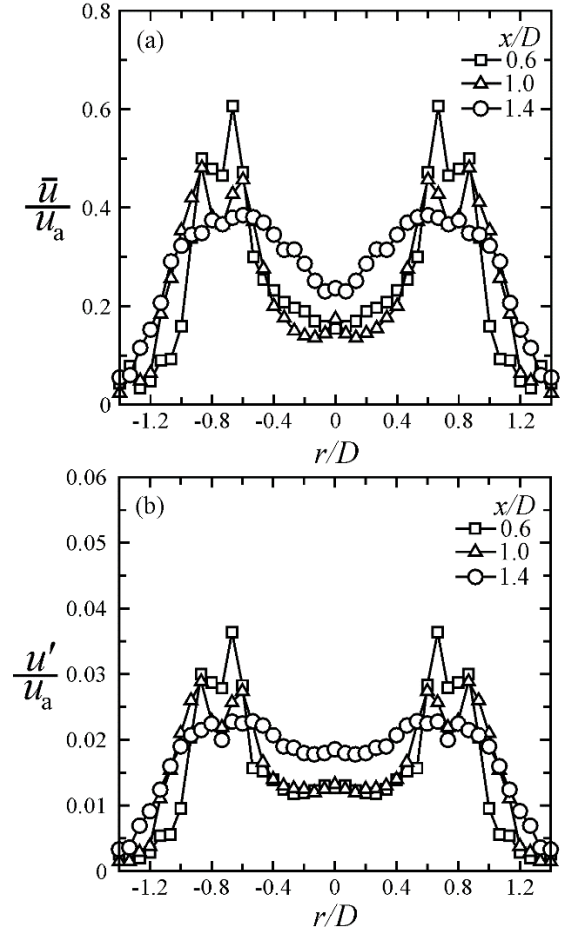


Figure 6. Radial distribution of axial velocity and turbulence intensity. $Re_a = 230, S = 0.207$

Figure 6 shows the normalized radial distribution of axial velocities ($\bar{u}/u_a$) and turbulence intensities (u'/u_a) at a typical central jet Reynolds number of $Re_c = 300$. The velocities are obtained at different axial distances of $x/D = 0.6, 1.0$, and 1.4 . They are normalized by u_a . In Figure 6(a), all the profiles of axial velocity $\bar{u}/u_a$ present twin peaks. The peak value of $\bar{u}/u_a$ decreases with

increasing axial distance x/D . For instance, $\bar{u}/u_a$ is about 0.62, 0.48, and 0.38 at $x/D = 0.6, 1.0$, and 1.4 , respectively. The peak values of $\bar{u}/u_a$ are located in the regions of the shear layer which are induced by the annular jet and the deflected central jet (i.e., $0.6 < r/D < 0.9$ and $-0.9 < r/D < -0.6$, respectively). At $-0.6 \leq r/D \leq 0.6$, the axial velocity $\bar{u}/u_a$ exhibits a decrease toward the central axis because of the control disk blocks the central jet flow. Inside the recirculation bubble (e.g., $x/D = 0.6$ and 1.0), the axial velocity is significantly smaller than that of the outer reverse flow zone (e.g., $x/D = 1.4$).

At $|r/D| \geq 0.9$, the axial velocity $\bar{u}/u_a$ decays rapidly when the radial distance increases. In Figure 6(b), the normalized axial turbulence intensities u'/u_a present a similar trend as shown in Figure 6(a) and the profiles feature outer and inner local maxima values. This feature can be explained as there are two inversion points linked to two rising profiles extending from the mean velocity peak values (Figure 6(a)). Each peak of the axial velocity profile induces two inversion points (i.e., outer and inner) [10]. These inversion points occurred around the shear-layer regions induced by the annular swirling jet (issued from the edge of blockage disk) and the deflected central jet (issued from the edge of the control disk). The maximum values of the turbulence intensity u'/u_a decrease when increasing the axial level. For instance, within the ranges of $0.6 < r/D < 0.9$ and $-0.9 < r/D < -0.6$, u'/u_a attains about 3.4%, 2.9%, and 2.3% at the axial distance of $x/D = 0.6, 1.0$, and 1.4 , respectively.

4. Conclusions

The flow behaviors, velocity, and fluctuation intensity distributions, and jet spreading properties of swirling jets (a case study of coaxial jets) were studied experimentally. The central jet fluids velocity was varied from low to high values in order to investigate the jet spreading. At low central jet Reynolds number (i.e., $Re_c \leq 200$), the central jet momentum is low and the annular jet passes over the blockage disk and dominates the flow field due to the annular jet dominated flow. However, when $200 < Re_c < 700$, the central jet is dominated by the flow field. The central jet is bent radially before rolling up and forming a toroidal wake in the downstream of the disks. The axial velocities and turbulence intensities along the central axis are significantly greater than those exhibited at $Re_c \leq 200$. The jet spread width increases gradually with an increase of Re_c . Consequently, this characteristic of jet spreading could enable fluid mixing to be improved eventually. As $Re_c < 700$, the shape of recirculation bubbles is maintained by the combined air entrainment and outer shear-layer of the annulus swirling flow. Operating the central jet Reynolds number at high values (i.e., $Re_c \geq 700$) causes the existence of a bifurcated jet with a large momentum. This deflected jet shoots radially far away from the control disk. Hence, there is no vertical structure found in downstream the control disk. In this case, the gap vortices appear in between the blockage and control disks because of the diffusion of the

central jet fluids. However, at a large radial distance, the shedding vortices occurred by combining the effects of both the shear layers induced by the bifurcated jet and the shear layer induced by the annulus swirling flow.

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NOMENCLATURE

CR	contraction ratio;
D	diameter of blockage disk, 30 mm;
d	diameter of central jet at exit, 5 mm;
D_c	diameter of control disk, 14 mm;
H	distance between two disks, 10 mm;
Re_a	Reynolds number of annular flow;
Re_c	Reynolds number of central jet;
r	radial coordinate;
S	swirl number;
u	instantaneous axial velocity;
$\bar{u}$	time-averaged axial velocity;
u'	axial velocity fluctuations;
u_a	mean axial velocity of annular swirling jet at exit;
u_c	mean axial velocity of central jet at exit;
w	azimuthal velocity;
x	axial coordinate.

REFERENCES

- [1] Schefer, R., Namazian, M., and Kelly, J., "Velocity measurements in turbulent bluff-body stabilized flows", *AIAA Journal*, 32(9), AIAA, 1994, 1844-1851.
- [2] Huang, R., and Lin, C., "Velocity fields of nonpremixed bluff-body stabilized flames", *Journal of Energy Resources Technology*, 122(2), ASME, 2000, 88-93.
- [3] Gupta, A. K., Lilley, D. G., and Syred, N., *Swirl flows*. Tunbridge Wells, Kent, England: Abacus Press, 1984.
- [4] Huang, R. F., and Tsai, F. C., "Observations of swirling flows behind circular disks", *AIAA Journal*, 39(6), AIAA, 2001, 1106-1112.
- [5] Yang, Y., and Kær, S. K., "Large-eddy simulations of the non-reactive flow in the Sydney swirl burner", *International Journal of Heat and Fluid Flow*, 36(1), Elsevier, 2012, 47-57.
- [6] Sieber, M., Paschereit, C. O., and Oberleithner, K., "Advanced Identification of coherent structures in swirl-stabilized combustors", *Journal of Engineering for Gas Turbines and Power*, 139(2), ASME, 2017, 021503.
- [7] Huang, R. F., and Yen, S., "Axisymmetric swirling vortical wakes modulated by a control disk", *AIAA Journal*, 41(5), AIAA, 2003, 888-896.
- [8] Mei, R., "Velocity fidelity of flow tracer particles", *Experiments in Fluids*, 22(1), Springer, 1996, 1-13.
- [9] Von Kármán, T., *Collected Works of Theodore Von Karman*, London, England: Butterworths Scientific Publications, 1956.
- [10] Tritton, D. J., *Physical fluid dynamics*. Springer Science & Business Media, 2012.