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Effects of area-ratio on the near-field flow characteristics and deflection of circular inclined coaxial jets

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ABSTRACT

An experimental study was carried out on 45° and 60° inclined coaxial jets, where secondary-to-primary jet area- and velocity-ratios were 4.0 and ranged from 0.5 to 2.0 respectively. Results reveal that the use of a relatively larger area-ratio here is able to suppress self-excited jet oscillations seen earlier in comparatively smaller area-ratio jets when velocity-ratio is 1.0. Flow visualization and PIV measurements demonstrate that this is due to the physically wider annular gap associated with a larger area-ratio. This reduces the extent to which primary and secondary ring-vortices can undergo vortex-pairing and merging seen in the previous study. Near-field centerline flow characteristics clarify the impact of area-ratio upon the flow fields, as well as its relationships with velocity-ratio and incline-angle. Unlike relatively smaller area-ratio jets, the effects of the velocity-ratio are found to be insignificant in the lower cases of 0.5 and 1 examined here. Correspondingly, primary jet deflections are found to be comparatively smaller for relatively larger area-ratio jets and significant only when velocity-ratio reaches 2.0. Lastly, jet velocity profile developments reveal that within the present measurement range, the two jet-streams in relatively larger area-ratio jets do not merge as rapidly as smaller area-ratio counterparts, particularly at a velocity-ratio of 2.0.

1. Introduction

The use of inclined exits on single-stream jet nozzles is a passive but viable technique to improve strategic controls over jet-mixing characteristics, as revealed by earlier studies performed by Wlezien and Kibens [31,32], Webster and Longmire [29], New [17] and New and Tsovolos [19]. For inclined circular jets investigated by Wlezien and Kibens [31,32], the resultant jet flows were dominated by the formation of inclined ring-vortices, which could undergo “turning” when the incline-angle used was significant. The mean effects of these occurrences manifested themselves as azimuthal redistributions of the shear layer energy, which would be useful for directional control over jet energy dissipation. On the other hand, a more fundamental look at the underlying flow behaviour of inclined circular jets by Webster and Longmire [29] revealed interesting correlations between the nozzle incline-angle, jet forcing frequency and the resultant jet characteristics. These studies subsequently prompted more recent investigations by New [17] and New and Tsovolos [19], where they observed suppression of axis-switching behaviour and rib-structures in major-plane inclined and minor-plane inclined elliptic nozzle jets respectively.

It should be mentioned at this point that jet nozzles with inclined exits remains a topic which has seen limited studies, as compared to other jet-mixing and control enhancement techniques. In particular, the flow influences exerted by inclined exits upon other alternative nozzle geometries are not well-understood. This consideration not only mooted investigations on inclined elliptic nozzles as discussed earlier, but it also led to a parallel effort on assessing the impact of inclined exits on circular coaxial nozzles by the authors, as reported in New and Tsioli [18]. Inclined circular coaxial jets can be treated as a logical extension of inclined circular jets, and the rationale is that certain fundamental aspects of the latter scenario should still remain. Despite the earlier investigations however, some questions surrounding the fundamental flow behaviour of inclined jets remain unresolved. This is also further complicated by additional flow parameters when coaxial jets are considered. In particular, the secondary-to-primary jet area-ratio and velocity-ratio are known to play important roles in determining the resultant flow behaviour.

Extensive experimental and numerical efforts on conventional non-inclined coaxial jets had been conducted in the past by Champagne and Wygnanski [8], Ko and Kwan [13], Kwan and

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Ko [14], Ribeiro and Whitelaw [22], Lu [15], Ko and Au [12], Au and Ko [2], Dahm et al. [9], Wicker and Eaton [30], Buresti et al. [7], Tang and Ko [26], Rehab et al. [21], Villermaux and Rehab [27], Warda et al. [28], Kiwata et al. [11], Sadr and Klewicki [23], Balarac and Métais [3], Talamelli and Gavarini [24], Balarac et al. [4] and Burattini and Talamelli [6], among others. These studies have shown that, on top of the area-ratio and velocity-ratio, other factors such as external flow excitations, initial velocity and turbulence distributions, as well as the nozzle lip thickness, also govern the resultant jet characteristics. Through these and other studies, variations in these parameters had been shown to produce different extents in their abilities to influence coaxial jet flows. The parallel effort reported in New and Tsioli [18], on the other hand, focused upon the influence of inclined exits on freely-exhausting coaxial jets, where only effects due to variations in the incline-angle and/or velocity-ratio were considered at that point.

In that study, fundamental flow dynamics of inclined coaxial jets were elaborated through a series of laser-induced fluorescence and particle-image velocimetry tests. A primary jet at a Reynolds number of Re = 2500 was used, where the coaxial jet area-ratio remained constant at $(D_2/D_1)^2 = 2.25$, and velocity-ratios of $U_2/U_1 = 0.5$, 1.0 and 2.0 were examined. Flow visualizations showed that the primary jet underwent regular oscillations about the incline-plane when velocity-ratio reached 1.0 and beyond, similar to single-stream inclined jets examined by Webster and Longmire [29] earlier. The result was a distinctive “serpentine”-shaped primary jet outline, first described by Webster and Longmire [29]. This phenomenon is due to jet oscillations produced by mutual interactions between inclined ring-vortices along both the primary and secondary jet shear layers. Visual evidence gathered during that study also indicated that the natures of jet oscillations at velocity-ratios of 1.0 and 2.0 were fundamentally different. Furthermore, as a result of the jet oscillations, the primary jet was found to deflect towards the longer nozzle length regions in a consistent manner with the extent of deflection increasing with the velocity-ratio and incline-angle used.

While New and Tsioli [18] had shed light upon the influences of the incline-angle and velocity-ratio in driving the underlying flow mechanisms in inclined coaxial jets, the role of area-ratio in inclined coaxial jets remains unresolved. In coaxial jets, the area-ratio directly impacts upon the extent of mutual interactions between the primary and secondary jet shear layer ring-vortices. While sufficiently small area-ratio coaxial jets produce intense mutual interactions that may lead to “lock-in” effects even in the near-field [9,25], it is expected that larger area-ratio coaxial jets are less likely to reproduce such behaviour. Any physical increase in the annular gap size should in theory serve to separate the two different trains of shear layer ring-vortices more and reduce the extent of mutual vortical interactions. Within the context of inclined coaxial jets here, this line of argument raises several outstanding questions. Firstly, how will the behaviour of primary and secondary jet ring-vortices differ in inclined coaxial jets with an area-ratio larger than that used by the preceding study? And secondly, what are the effects of velocity-ratio and incline-angle variations upon inclined coaxial jets with a larger area-ratio? Thirdly and perhaps more importantly, how will the use of a larger area-ratio impact upon previously observed jet deflection behaviour in inclined coaxial jets? To address these queries, further experiments have therefore been carried out on inclined coaxial jets based on a larger area-ratio. For a consistent comparison, all initial flow conditions, parameters, experimental techniques and procedures between this and preceding study, with the exception of the area-ratio, remained the same.

2. Experimental setup and procedures

2.1. Experimental apparatus

The experimental setup consisted of a flow-conditioning coaxial jet apparatus attached to one of the walls of a recirculating horizontal water-tank, similar to the one used by New and Tsioli [18]. The water tank measured 1000 mm $(L) \times 400$ mm $(W) \times 400$ mm (H) and was fabricated entirely from clear 15 mm thick Plexiglas sheets. Coaxial jets were produced by two separately-controlled centrifugal pumps driving water into the jet apparatus, where their flow rates were controlled using valves and electromagnetic flow meters. The jet apparatus consisted of two concentric stainless-steel and brass sub-apparatus: one for the primary jet and one for the secondary jet. The sub-apparatus possessed diffuser, flow-straightening honeycomb structures, layers of fine screens and contoured contraction chambers for conditioning two separate streams of water flows before they were issued from the test nozzles into a quiescent reservoir in the water tank. To ensure a constant water height, overflow from the exhausting coaxial jets was redirected into a small water reservoir via PVC tubing located near the top of the water-tank end wall. Water from this reservoir was then recirculated by the centrifugal pumps to complete the flow circuit.

2.2. Coaxial jet nozzles and flow conditions

Two sets of inclined coaxial nozzles (incline-angles of 45° and 60°) were used for this series of experiments. These incline-angles were similar to those tested in the earlier study by the authors. The diameter of the primary jet nozzle measured $D_1 = 20$ mm (similar to previous study), while that of the secondary jet nozzle measured $D_2 = 40$ mm. Unlike the earlier study however, the area-ratio of the inclined coaxial nozzles studied here was $\mathrm{AR} = (D_2/D_1)^2 = 4.0$, which was almost twice as large. The ratio of the annular secondary jet cross-section area to that of the circular primary jet was 2.79 for the present inclined coaxial nozzles. In contrast, the corresponding cross-sectional area-ratio for the previous study was 1.04. Regardless of which definition was used, it is quite clear that the present inclined coaxial nozzles have a significantly larger area-ratio. Nozzle wall thickness was maintained at $t_w = 1$ mm throughout.

The two sets of inclined coaxial nozzles shared a common mean height (i.e. the average of shorter and longer nozzle lengths for each nozzle) with those used in the previous study, which was $H/D_1 = 2.5$. As the axial lengths of the inclined coaxial nozzles varied continuously along their circumferences, the use of a mean height represented a more consistent way of locating a pseudo jet-origin. Fig. 1 shows the designs and relevant dimensions of the 45° and 60° inclined coaxial nozzles as an illustration. The mean velocity of the primary jet was maintained at $U_1 = 0.14$ m/s, while the velocity-ratios used were $U_2/U_1 = 0.5$, 1.0 and 2.0. This translated into a Reynolds number of approximately $\mathrm{Re}_1 = U_1 D_1/\nu = 2500$ for the primary jet, where ν is the kinematic viscosity of water at experimental conditions. As for the secondary jet, its Reynolds number ranged from $\mathrm{Re}_2 = U_2 d/\nu = 500$ to 2000 for the velocity-ratios tested, where d is the annular gap size between the secondary and primary jet nozzles. These conditions were selected to match those used in New and Tsioli [18] and the initial jet exit velocity profiles taken at $x/D_1 = 0.3$ distance away from and perpendicularly across the nozzle exits for a set of non-inclined coaxial nozzles (not shown here) with the same area-ratio at the velocity-ratios used are shown in Fig. 2.