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FLOW CONTROL USING ANNULAR JETS

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INTRODUCTION

Turbulent jets that issue into quiescent uniform environments are a well-studied class of turbulent shear flow [1, 2]. Our interest here is in the airflow created by annular jets from sources comprised of a thin slot wrapped into a circular annulus, with a slot gap considerably smaller than the annulus diameter, $h \ll D$. One example of a practical application of this source configuration is the Dyson Air Multiplier Fan. Whilst there are many studies on so-called 'unventilated' annular jets, namely, those with a solid surface within the annulus [3], since this configuration relates to gas turbines or similar turbomachinery, there are relatively few studies on 'ventilated' annular jets. Ventilated sources have a hole through the centre of the annulus, *e.g.* as depicted in Fig. 1(right), so that ambient air can be drawn through the device. Entrainment into this jet and the pattern of airflow induced are modified because the annulus is ventilated, and thus ventilating the nozzle offers a potentially effective form of flow control.

To improve our understanding of ventilated annular jets, in this study we compare the flow of a classic turbulent round jet to an annular jet of equal nozzle area. Measurements in the near- and far- fields of both jets are presented and we discuss key features of the flow, including flow rate modification and shift in the virtual origin.

EXPERIMENTAL SETUP

The turbulent round jet source used was nearly identical to that used in the study by Hussein, Capp & George [4]. The source was of diameter d = 25.4 mm with a 121:1 contraction ratio nozzle and upstream flow conditioning (honeycomb and 3 mesh screens). This ensured an approximately top-hat exit velocity profile and low initial turbulence. The annular jet had a slot gap of h = 1.6 mm, centred on a diameter D = 100 mm, so that the exit area was equal to that of the round jet. The annulus apparatus was 70 mm long and had an internal cavity of 10 mm width. The annular source was fed and supported from 4 locations around the annulus. Both nozzles were rapid prototyped using SLA material and are shown in Figure 1.

The circular and annular nozzles were supplied with air from a variac controlled centrifugal fan. The supply flow rates were measured with a calibrated bell mouth. The round jet was studied with a source flow rate of Q_0 = 28.8 lps giving a horizontal exit velocity of approximately U_0 = 56.8 m/s and a Reynolds number based on the source diameter of $\mathrm{Re}_d = U_0 d/\nu$ = 95,000. The annular jet was studied at Q_0 = 14.4 lps so that U_0 = 27.8 m/s and a Reynolds number based on the slot gap of $\mathrm{Re}_h = U_0 h/\nu$ = 3,000.

All experiments were conducted in a laboratory of dimensions 5 x 3 x 3 m^3. Particle Image Velocimetry (PIV) was used to measure the flow in vertical planes at distances

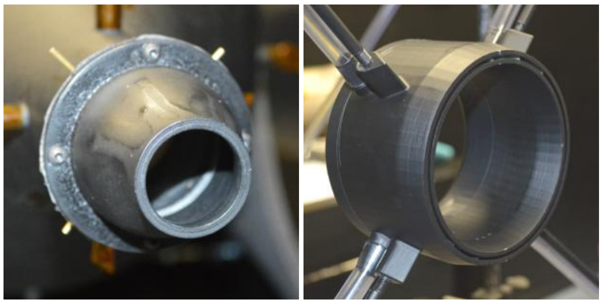

Figure 1. Jet nozzles. Round (left). Ventilated annular (right).

along the centreline of up to 2 m from each source. Five fields-of-view were measured, ranging from 165 x 140 mm in the near-field to 750 x 620 mm in the far-field. Interrogation windows ranged from 2.1 x 2.1 mm^2 to 9.5 x 9.5 mm^2 accordingly (32 x 32 pixels), with a 50% overlap. PIV fields were acquired at 15 Hz, where 500 (round jet) and 1250 (annular jet) fields were acquired for obtaining estimates of time-average quantities and turbulence statistics.

JET NEAR-FIELD

The mean velocity and turbulent kinetic energy in the near-field of the round and annular jets are presented in Figure 2 (TKE assumes $v'^2 = w'^2$).

Results for the round jet agree well with established results, *e.g.* those of [2]. The round jet exits with an approximately uniform velocity distribution. Instabilities subsequently initiate in the shear layers at the jet edges which slowly penetrate into the core of the jet. A potential core exists for 5-6d downstream of the nozzle exit, after which the flow is fully turbulent. Entrainment takes place on the outer edges of these shear layers so that ambient fluid is drawn from all around the jet to increase its flow rate with distance.

The ventilated annular jet shows qualitatively different behaviour. The section through the flow field depicted in Figure 2 shows the jet issuing from the upper and lower portion of the annulus in a manner similar to a planar jet, spreading and decaying accordingly. External fluid from the environment is drawn in towards the annular jet due to turbulent entrainment into the outer perimeter. For both annular and round jet, near vertical streamlines can be seen to connect the induced flow in the ambient with the jet flow itself (Figs. 2a)ii) and b)ii)). However, for the annular jet entrainment also occurs at the inner perimeter of the jet which leads to stark differences in the behaviour and development of the two flows. This 'inner' entrainment (apparent for $x/D \lesssim 1$) induces a flow of ambient fluid in through the open (ventilated) annulus to replace the entrained fluid. This results in a non-zero streamwise velocity component inside the annulus, thereby "amplifying" the apparent source flow rate,

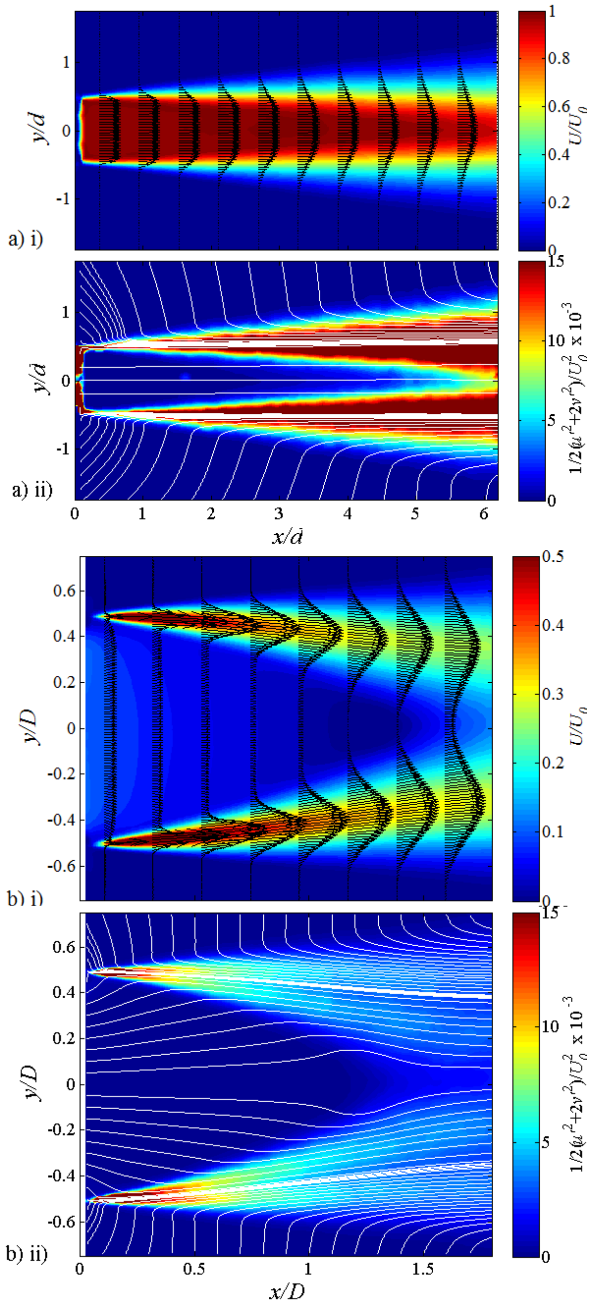

Figure 2. a) Round jet; b) Annular jet. i) Mean streamwise velocity; ii) Turbulence kinetic energy (TKE).

i.e. the flow rate at the vertical plane of the source. For $x/D > 1$ the jet begins to entrain itself so that the upper and lower portions of the jet seen in Fig. 2b are drawn towards the centreline. These then begin merging further downstream, finally forming a round jet.

JET FAR-FIELD

Comparison of the far-field development of the two jets is non-trivial, since the annulus exhibits two length scales, h and D, whilst the round jet has a single length scale, d. To compare the flows, we choose as a length scale $l_q = Q_0/M_0^{½} = \sqrt{A_0}$ [5], so that for the round jet $l_q = \sqrt{(\pi/4)}d = 0.89d$.

Figure 3a plots the centreline velocity, U_c, for the round and annular jets (note that a linear increase of U_0/U_c with x implies the velocity decays as $U_c \sim 1/x$). Our round jet data

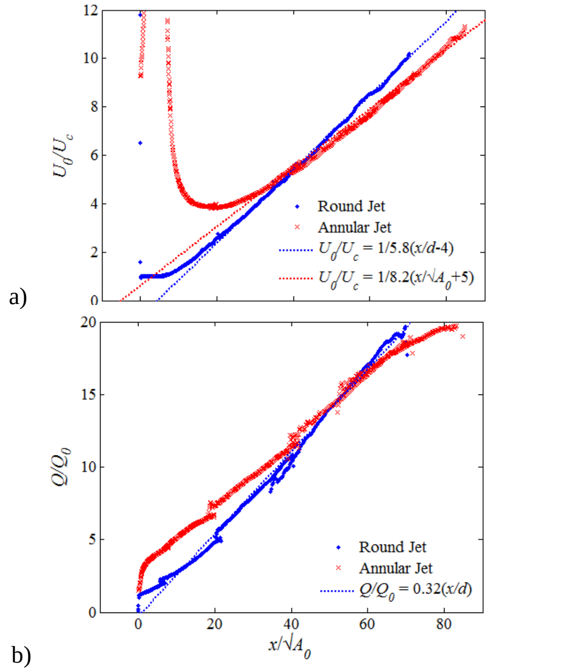

Figure 3. a) Velocity decay. b) Volumetric flow rate.

follows, almost exactly, the velocity decay profile proposed in [4], exhibiting a virtual origin at $4d$ in front of the nozzle and a decay constant of 5.8. By contrast, the annular jet exhibits a decay constant of 8.2, indicating that the decay of the ventilated annular jets centreline velocity is not as rapid as the round jet. Furthermore, there is a shift in virtual origin to $5\sqrt{A_0}$ *behind* the annulus. Thus, the annular jet shifts the virtual origin upstream, promoting jet development, though the growth rates and origin are relatively sensitive to alignment of PIV fields and is being investigated in ongoing work.

The volume flow rate enhancement by an annular jet is also evident in Figure 3b, where the flow rates were estimated from the centreline PIV assuming axi-symmetry. The annular jet has more than double the flow rate of the round jet for $x/\sqrt{A_0} < 20$. An immediate implication is that a device with a ventilated-annular geometry will provide higher flow rate than a circular source (of the same area) for an identical input flow.

CONCLUSIONS

The ventilated annular jet has been compared to a round jet with top-hat exit velocity profile. We find that the annular geometry shifts the virtual origin upstream of the device, whilst exhibiting slower decay rate and a boost in flow rate near the source. In the conference we will present further phenomenon and discuss the flow rate enhancement along with jet length scales.

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