NEAR FIELD ROUND JET FLOW DOWNSTREAM FROM AN EXTENDED ABRUPT CONTRACTION NOZZLE

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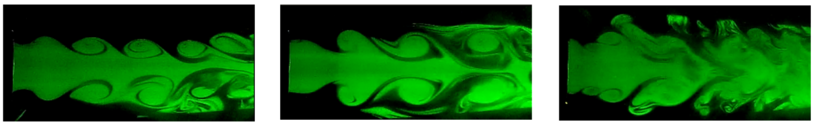
Abstract Round air jet development downstream from an abrupt contraction coupled to a uniform circular tube extension with length to diameter ratio $L/D = 1.2$ and $L/D = 53.2$ is studied experimentally. Smoke visualisation and systematic hot film velocity measurements are performed for low to moderate Reynolds numbers $1130 < Re_b < 11320$. Mean and turbulent velocity profiles are quantified at the tube exit and along the centerline. Flow development is seen to be determined by the underlying jet structure at the tube exit which depends on Reynolds number, initial velocity statistics at the tube exit and the presence/absence of coherent structures. It is shown that the tube extension ratio L/D as well as the sharp edged abrupt contraction influence the initial jet structure at the tube exit. For both L/D ratios, the presence of the abrupt contraction results in transitional jet flow in the range $2000 < Re_b < 4000$ and in flow features associated with forced jets and high Reynolds numbers $Re_b > 10^4$. The tube extension ratio L/D downstream from the abrupt contraction determines the shear layer roll up so that for $L/D = 1.2$ flow visualisation suggests the occurrence of toroidal vortices for $Re_b < 4000$ whereas helical vortices are associated with the transitional regime for $L/D = 53.2$. Found flow features are compared to features reported in literature for smooth contraction nozzles and long pipe flow.

NEAR FIELD FLOW VISUALISATION

A qualitative description of the flow development is given based on flow visualization as illustrated in Fig. 1. For the



(a) $Re_b = 1131$, $L/D = 1.2$ (b) $Re_b = 1697$, $L/D = 1.2$ (c) $Re_b = 2829$, $L/D = 1.2$

(d) $Re_b = 1131$, $L/D = 53.2$ (e) $Re_b = 1697$, $L/D = 53.2$ (f) $Re_b = 2829$, $L/D = 53.2$

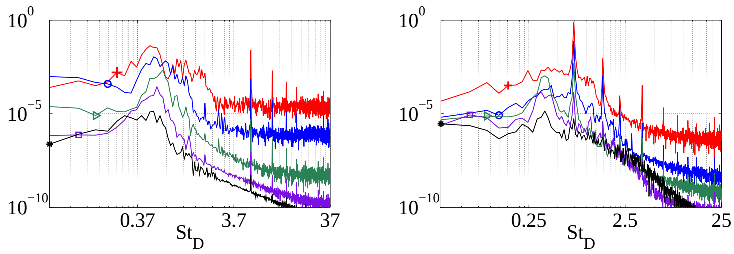
Figure 1. Instantaneous images of jet flow in the near field downstream the pipe nozzle, *i.e.* $0 \leq x/D \leq 5$.

long pipe nozzle, $L/D = 53.2$, a jet flow instability emerges at Reynolds number $Re_b = 2263$ in accordance with the helical nature of laminar pipe flow for $L/D > 40$ [2, 5, 1]. The onset of instabilities in the range $2000 < Re_b < 3000$ is in accordance with observations of pipe flow issuing from a smooth long pipe nozzle in case a large disturbance is introduced at the inlet [5]. Therefore, the presence of an abrupt contraction at the pipe inlet can be seen as a geometrical disturbance reducing the Reynolds numbers associated with the transition regime compared to transitional Reynolds numbers $Re_b \approx 10^4$ observed for pipe flow in absence of such disturbances [5].

For $L/D = 1.2$, the flow structure depends on Reynolds number. For low $Re_b = 1131$ the interaction of large scale structures and their deformation in the near field is limited. The presence of the abrupt contraction triggers the shear layer roll up at the nozzle exit so that generation of ring vortices is shifted upstream compared to a smooth contraction nozzle [4]. For $Re_b = \{1697, 2263, 2829\}$ a smaller tailing vortex is observed immediately behind a large leading vortex at $x/D \approx 1$. The collapse of the two vortices into a single one at $x/D \approx 2$ suggests a vortex pairing process to take place at a spatial position observed for transitional jet flow at high Reynolds numbers $Re_b > 10^4$ as described by the two ring model for the axisymmetric jet issuing from a smooth contraction nozzle [3]. At $Re_b = 3961$, large scale vortex formation and pairing are still observable. Nevertheless, the structure coherence is less evident than for lower Reynolds numbers. Increasing the Reynolds number beyond $Re_b = 4000$ has for effect to limit the vortex size, and to quickly destroy them resulting in turbulent flow.

SPECTRAL ANALYSIS OF THE VELOCITY SIGNAL

The power spectral density of the velocity signal is illustrated for $L/D = 1.2$ in Fig. 2. The centerline spectra obtained for $L/D = 1.2$ are characterised by broad and sharp frequency peaks for which the spectral position and amplitude vary as function of Reynolds number Re_b and measurement station x/D. For $Re_b = 1131$, the spectra exhibit a broad frequency



(a) $L/D = 1.2$, $Re_b = 1131$ (b) $L/D = 1.2$, $Re_b = 1697$

Figure 2. Power spectra of centreline velocity signals at $x/D = 1$ (+), $x/D = 2$ (○), $x/D = 3$ (▷), $x/D = 4$ (□), $x/D = 5$ (∗).

peak at approximately 14 Hz, corresponding to Strouhal number $St_D \approx 0.55$ for all measurement stations $1 \leq x/D \leq 5$. The amplitude of the broad peak amplifies as x/D increases to $x/D = 3$ and reduces at $x/D = 5$. The broad peak is associated with the roll up of the initial vorticity sheet into a toroidal vortex ring. The maintenance of the peak, regardless x/D, confirms the quasi stability of coherent structures for $Re_b = 1131$ as observed from flow visualisation in Fig. 1. For $Re_b = 1697$, a sharp peak at 30 Hz appears comparable to those observed in the jet shear layer. In addition, harmonics are observed at $x/D = 1$ and $x/D = 2$. The presence of this sharp energy peaks in the centerline power spectrum confirms the formation of vortices and the convection of surrounding vortices at specific frequencies. A broad subharmonic emerges at approximately 15 Hz at $x/D \geq 3$ along with a reduced amplitude of the sharp energy peak and the disappearance of the harmonics. The appearance of the subharmonic is associated with the pairing of two ring vortices illustrated in Fig. 1. The general tendencies outlined for $Re_b = 1697$ are also observed for $2263 \leq Re_b \leq 3961$. The frequency of the peaks shifts to higher frequencies as the Reynolds number increases corresponding to an acceleration in the vortex generation resulting in increased instability and interaction of the coherent structures so that the amplitude of the peaks varies with Reynolds number. For $Re_b = 2263$ the amplitude of the peaks increases due to the reduced central jet portion so that the centerline velocity is most influenced by the passing of coherent structures and their interaction. For $2263 < Re_b \leq 3961$ the amplitude of the peaks, sharp as well as broad, gradually decreases so that for $Re_b = 2829$ the velocity spectrum is flattened out at $x/D = 5$. For $Re_b = 3961$ the spectra are flattened out at $x/D = 4$ and $x/D = 5$ resulting in spectra characteristic for turbulent flow. Finally, for $Re_b = 11317$ all spectra are flattened out, so that no well defined sharp peaks are observed.

CONCLUSION

The presence of an abrupt contraction at the nozzle inlet disturbs and forces the flow so that the jet becomes transitional for low Reynolds numbers in the range $1131 < Re_b < 4000$ for both assessed length to diameter ratios. As a consequence, the near field behaviour is dominated by the generation, passage and interaction of large flow structures associated with transition which results in a peak value of the initial centerline turbulence intensity $T_{U,0}$ around $Re_b \approx 2263$. For $Re_b > 2263$, the structures start to break down so that for higher Reynolds numbers $Re_b > 4000$ the jet dynamics becomes similar to observations made for high Reynolds numbers $Re_b > 10^4$ indicating that the jet dynamics becomes mainly determined by flow inertia and backflow.

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