Experimental Investigations on Mixing Evaluation in Non-Circular Sharp Edge Nozzles

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Abstract An experimental study using Particle Image Velocimetry (PIV) on free jets issuing from sharp edge nozzles having different cross-section geometries is reported: elliptical, square, rectangular and triangular. The mixing efficiency of each nozzle is quantified at large and small scales. In respect to the large scales contribution, the definition of mixedness is used, while for small-scales, the entropy generation concept is employed. These quantities are computed to evaluate the mixing efficiency in the near field and interaction zone ($0<X/D<18$) of each nozzle. The effect of Reynolds number on the differences among the nozzle shapes is also discussed by performing measurements just after the laminar-turbulent transition (Re=8000) and in the fully turbulent regime (Re=35000). The results are also compared to the circular nozzle data to define changes in mixing efficiency among axisymmetric and asymmetric nozzles. The results show significant differences on major and minor axis of nozzles confirming the presence of axis switching features for elongated nozzles (elliptical and rectangular). Specifically, axis switching improves small scale mixing efficiency locally in the nozzle near field, while being less efficient in the far field in comparison to circular and square nozzles.

EXPERIMENTAL FACILITY

A schematic view of the experimental test-rig and four images of high quality manufactured non-circular nozzles are shown in Figure 1 on the left and right parts respectively. Water coming from a constant level container continuously flows from the inlet chamber into a larger chamber (transverse size equal to about 30D) and through the nozzles to the downstream wide chamber before going to the ground container. Five different nozzles are considered in the experiment: circular, rectangular, squared, elliptical and triangular. The nozzle area is fixed for all nozzles and is equal to the area of circular orifice used for comparison (diameter D=2cm). The whole test section is made by Plexiglas to allow optical access. The flow rate is measured by an ultrasound flow meter with an error of ±2.5%. The two tested velocities allow to derive Reynolds numbers, based on the jet diameter, equal to 8.000 and 35.000.

The flow is seeded by hollow glass particles with average diameter of 10 μm and illuminated by a Nd-Yag pulsed laser (200 mJ/pulse) with 1 mm laser sheet thickness. The time delay between two pulses is 1 ms and the time interval between two pulses is optimized accordingly to the camera frame rate. The images are acquired by a high-speed camera with 1024×1024 pixel resolution at 2000 fps and stored for processing. The PIV image analysis is performed by the LaVision Davis software and by averaging the data over the minimum window size of 32×32 pixels with 75% overlapping resulting in 128×128 grid points. For capturing higher resolution images, the region of the jet from X/D=0 to X/D=20 is subdivided into five parts. The dimensions of each part are 8 cm × 8 cm which provides the minimum resolution of 0.078 (mm/pixel). The overlap between two adjacent windows is 2 cm to avoid border effects in final PIV post processing and consequent spurious vectors. In every part of the jet, 10.000 sample images are acquired for each nozzle type: the derived statistical accuracy is around 0.3% for mean and *rms* values.

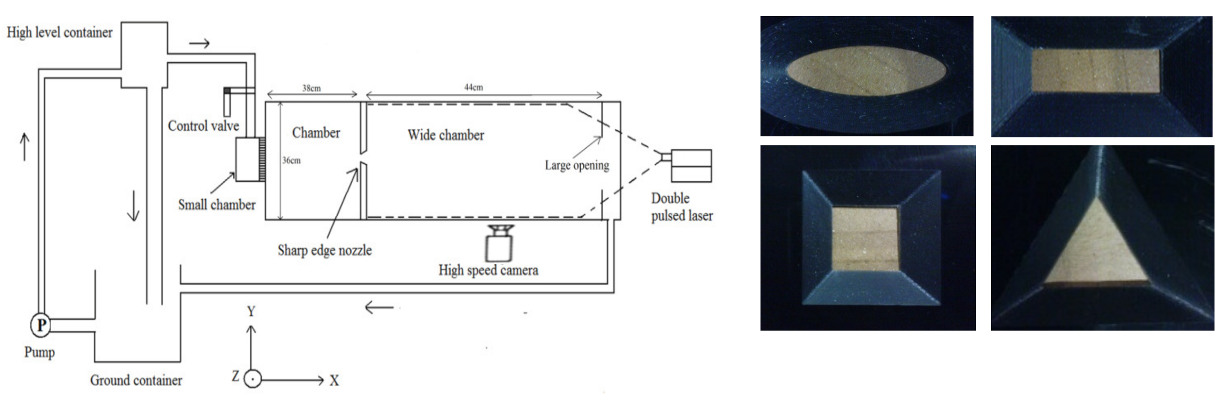

Figure 1. Schematic of experimental facility with sample illumination along X-Y plane (on the left) and images of high quality manifactured non-circular nozzles (on the right).

RESULTS

The mixedness is evaluated as in Cetegen & Muhamad [1], but using the velocity rather than concentration field, whereas entropy generation is evaluated as in Naterer & Adeyinka [2]. The former is based on mean velocity data (*i.e.* related to large-scale mixing), while the latter on mean-square velocity derivatives (*i.e.* related to small-scales). Contours of these quantities for the elliptic nozzle (on the minor axis plane) are shown in Figure 2 for the first three regions at Re=8.000. It is clearly seen the abrupt increase of mixedness around *X/D*=1-2 due to the first axis switching (on the left). From this region, mixing is quickly increased laterally to the entire field where values even larger than that at the exit are measured. On the other hand, for entropy generation, the area of larger values is confined before the axis switching while decaying very fast by moving downstream (down to 10% of the initial value at *X/D*≈6).

This can be seen more quantitatively in Figure 3, where mixedness and entropy generation for all jets at Re=35.000 are compared, some of them being measured on both the major and minor axis planes. The data are taken at the half-width distance from the axis, evaluated separately for each geometry. The results of mixedness (on the left) indicate that circular and square nozzles have similar behaviors reaching the highest mixing in comparison to other nozzles. The elliptical and rectangular jets are also similar between them no matter if major or minor axis is considered (except for *X/D*<6), whereas the triangular jet reaches intermediate values among the two groups. On the other hand, entropy generation seems to be very similar for all jets (right part of figure 3). However, for *X/D*>6, as shown in the insert, there are again larger values from circular and square nozzles in comparison to others.

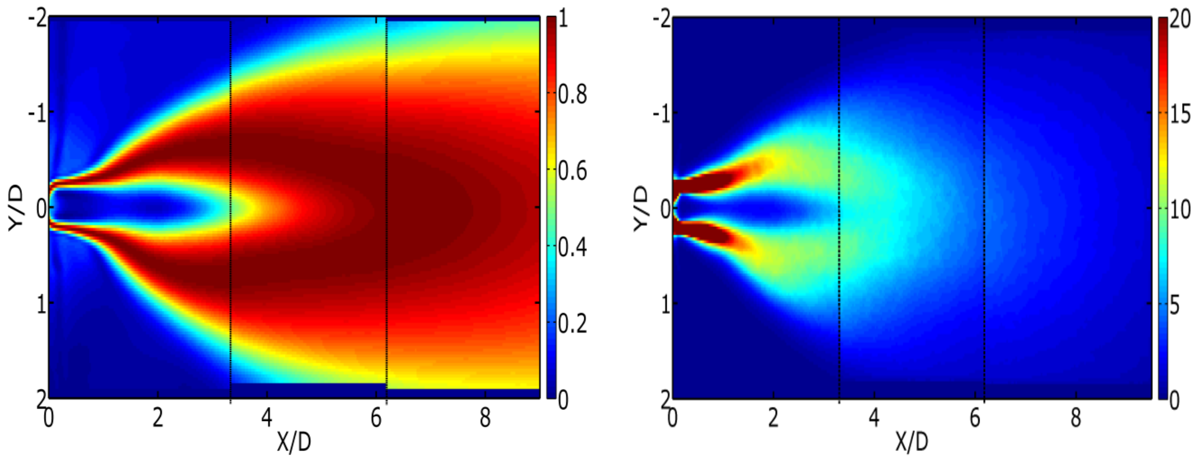

Figure 2. Mixedness (left) and entropy generation (right) contours for elliptic nozzle in minor axis plane for Re=8000.

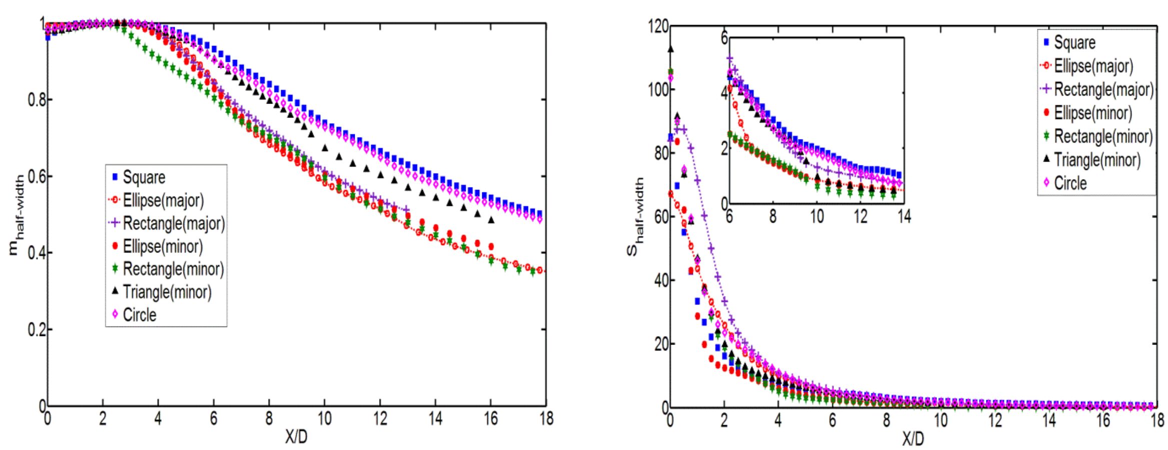

Figure 3. Half-velocity width evolution of mixedness (on the left) and entropy generation (on the right) for Re=35000.

References

[1] Cetegen, B. M., Mohamad, N., Experiments on liquid mixing and reaction in a vortex. J. Fluid Mech. **249**, 391-414, 1993.

[2] G. F. Naterer and O.B. Adeyinka. Imaging velocimetry measurements for entropy production in a rotational magnetic stirring tank and parallel channel flow. Entropy. **11**, 334-350, 2009.