# Starting Vortex Identified as Key to Unsteady Ejector Performance

Unsteady ejectors are currently under investigation for use in some pulse-detonation-engine-based propulsion systems. Experimental measurements made in the past, and recently at the NASA Glenn Research Center, have demonstrated that thrust augmentation can be enhanced considerably when the driver is unsteady. In ejector systems, thrust augmentation $\bullet$ is defined as $\bullet = T^{Total}/T^{j}$, where T^{Total} is the total thrust of the combined ejector and driving jet and T^{j} is the thrust due to the driving jet alone.
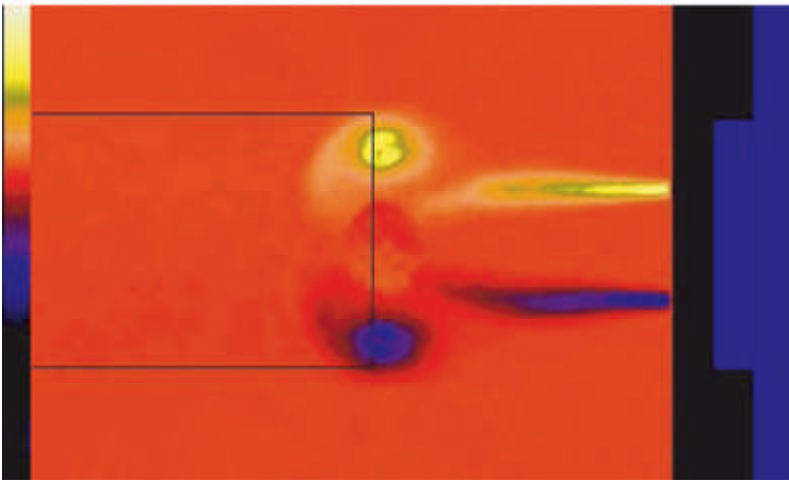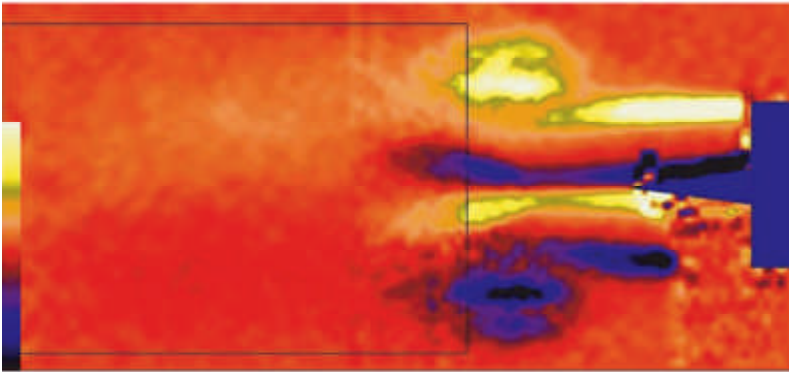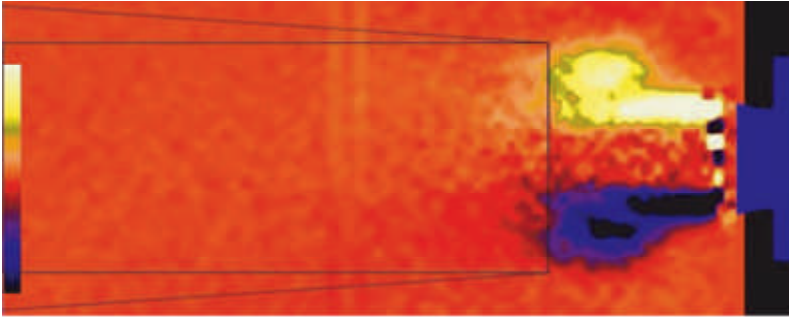
Ensemble-averaged contours of measured instantaneous vorticity for three pulsed thrust sources. Measurements were made using digital particle imaging velocimetry. Top: 220-Hz pulsejet. Center: 275-Hz resonance tube. Bottom: 50-Hz speaker-driven jet.

There are three images in this figure, one for each of the named thrust sources. The images are color contours of measured instantaneous vorticity. Each image is an ensemble-average of at least 150 phase-locked measurements. The flow is from right to left, and the shape and location of each driver is shown on the far right of each image. The emitted vortex is a clearly defined "doughnut" of highly vortical (spinning) flow. In these planar images, the vortex appears as two distorted circles, one above, and one below the axis of symmetry. Because they are spinning in the opposite direction, the two circles have

vorticity of opposite sign and thus are different colors. There is also a rectangle shown in each image. Its width represents the ejector diameter that was found experimentally to yield the highest thrust augmentation. It is apparent that the optimal ejector diameter is that which just "captures" the vortex: that is, the diameter bounding the outermost edge of the vortex structure.

The exact mechanism behind the enhanced performance is unclear; however, it is believed to be related to the powerful vortex emitted with each pulse of the unsteady driver. As such, particle imaging velocimetry (PIV) measurements were obtained for three unsteady drivers: a pulsejet, a resonance tube, and a speaker-driven jet. All the drivers were tested with ejectors, and all exhibited performance enhancement over similarly sized steady drivers. The characteristic starting vortices of each driver are shown in these images. The images are color contours of measured instantaneous vorticity. Each image is an ensemble-average of at least 150 phase-locked measurements. The flow is from right to left. The shape and location of each driver is shown on the far right of each image. The rectangle shown in each image represents the ejector diameter that was found experimentally to yield the highest thrust augmentation. It is apparent that the optimal ejector diameter is that which just "captures" the vortex: that is, the diameter bounding the outermost edge of the vortex structure.

Although not shown, it was observed that the emitted vortex spread as it traveled downstream. The spreading rate for the pulsejet is shown as the dashed lines in the top image. A tapered ejector was fabricated that matched this shape. When tested, the ejector demonstrated superior performance to all those previously tested at Glenn (which were essentially of straight, cylindrical form), achieving a remarkable thrust augmentation of 2. The measured thrust augmentation is shown in the following graph as a function of ejector length. Also shown on the plot are the thrust augmentation values achieved with the straight, cylindrical ejectors of varying diameters.
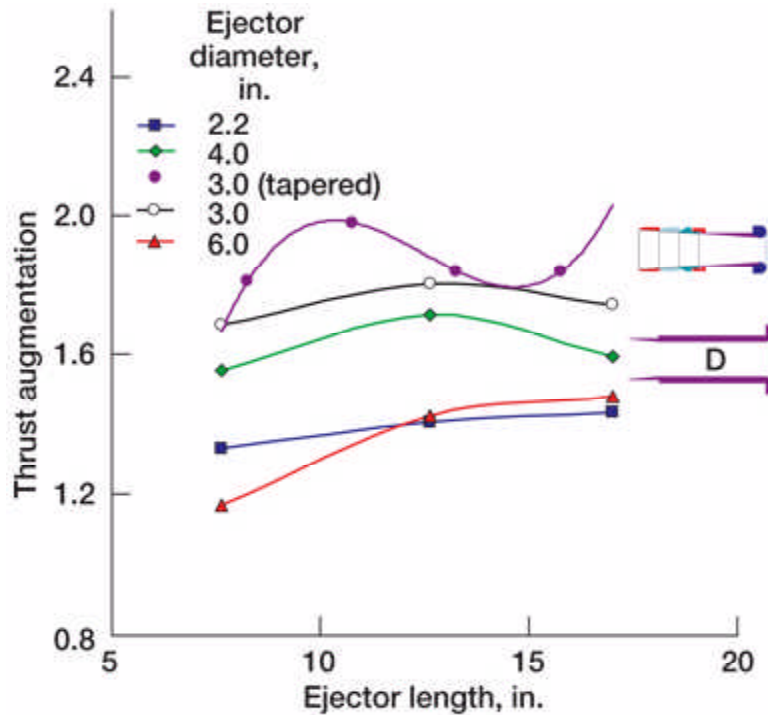
Measured thrust augmentation as a function of ejector length for the tapered and straight ejectors. Each curve represents a different ejector diameter. The driver is a pulsejet. Here, thrust augmentation is plotted as a function of ejector length for several families of ejector diameters. It can be seen that large thrust augmentation values are indeed obtained and that they are sensitive to both ejector length and diameter, particularly the latter. Five curves are shown. Four correspond to straight ejector diameters of 2.2, 3.0, 4.0, and 6.0 in. The fifth curve corresponds to the tapered ejector contoured to bound the emitted vortex. For each curve, there are several data points corresponding to different lengths. The largest value of thrust augmentation is 2.0 for the tapered ejector and 1.81 for the straight ejectors. Regardless of their diameters, all the ejectors trend toward peak performance at a particular length.

That the cross-sectional dimensions of optimal ejectors scaled precisely with the vortex dimensions on three separate pulsed thrust sources demonstrates that the action of the vortex is responsible for the enhanced ejector performance. The result also suggests that, in the absence of a complete understanding of the entrainment and augmentation mechanisms, methods of characterizing starting vortices may be useful for correlating and predicting unsteady ejector performance.

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