Undergraduate Studies of Supersonic Flow From a Converging-Diverging Nozzle

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Abstract

Undergraduate studies are carried out to examine the supersonic flow from an axisymmetric converging-diverging nozzle. Flow in the nozzle is initiated by the rupture of a Mylar® diaphragm that is positioned between the nozzle and a 1-gallon pressurized air tank. Flow exits the nozzle into standard atmospheric conditions. Simulations are carried out in COMSOL Multiphysics® for unsteady, axisymmetric flow with the High Mach Number interface of the CFD Module. Adaptive meshing is utilized to capture the structure of the flow, including the initial shock wave and the Mach diamonds that are present after the flow from the nozzle has been fully established. Qualitative and quantitative comparisons are made to the COMSOL simulation with experiments based on high-speed video shadowgraph imaging and dual-beam interferometry measurements. At Bethel University, fluid mechanics is integrated into the physics and engineering programs through an introductory course in fluid mechanics that incorporates laboratory and computational components. In recent years, student projects have been carried out to study a number of applications involving compressible flows and shock waves [1, 2]. Here, the CFD module serves to enrich the supersonic nozzle studies. COMSOL is also used to complement experiments in a variety of projects in areas other than fluid mechanics [3].

Figures 1-2 show a comparison of the startup flow for a shadowgraph sequence at 100,000 frames per second and the COMSOL simulation. The sequence depicts the initial 140 microseconds of the flow (10 microseconds between frames), beginning with the exit of the initial shock wave from the nozzle and portraying the development of the initial flow and Mach diamond formation. The features in the shadowgraph images are a result of refractive index variations due to density variations in the flow field, with the dark features corresponding to regions with a strong density gradient. The corresponding images from the COMSOL simulation display the magnitude for the gradient of the density field. The COMSOL images are mirrored for comparison to the shadowgraph images and use a grayscale map, with the dark regions corresponding to the large density gradients. The simulation clearly captures the structure for the initial shock structure and flow field from the nozzle.

Dual-beam interferometry allows a quantification of the density variations in the nozzle flow as function of time. A heterodyne interferometer (using a stabilized He-Ne laser's 633 nm wavelength) measures changes in the optical path due to fluid density fluctuations by recording phase shifts between two 80 MHz reference signals [1]. A relative phase shift of 2 pi thus corresponds to 633 nm optical path change along the round-trip laser beam's path through the

fluid. Quantitative comparisons between the interferometric measurements and COMSOL simulations will be presented.

Reference

1. G. Olson, , et al., “The role of shock waves in expansion tube accelerators,” American Journal of Physics, 74 (2006) 1071-1076.
2. K. Stein, “Fluid Mechanics and Computational Physics in the Advanced Undergraduate Laboratory, Proceedings of the AAPT Topical Conference on Advanced Laboratories, Ann Arbor, Michigan (2009).
3. K. Stein, et al., “Resonating with Students in the Undergraduate Physics Laboratory: Comprehending Acoustic Vibrations,” COMSOL Conference, Boston, Massachusetts (2008).

Figures used in the abstract

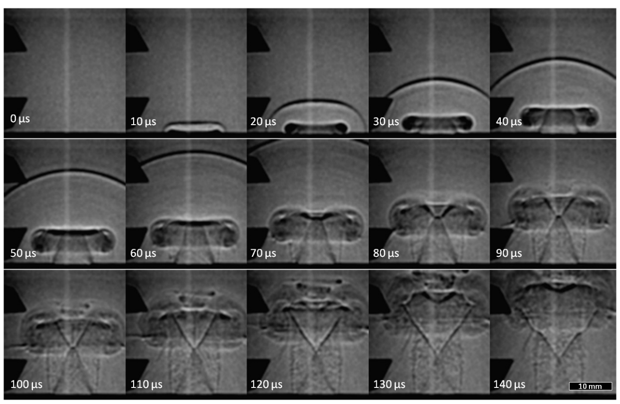

Figure 1: High-speed video shadowgraph image sequence depicting the initial shock wave and the formation of the Mach diamonds at the exit of the nozzle.

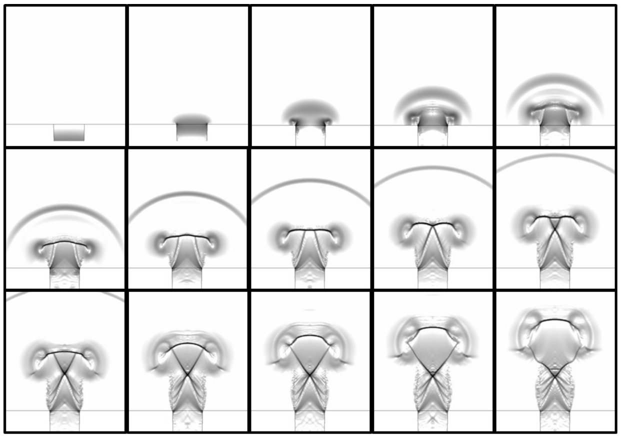

Figure 2: Sequence of images from the COMSOL simulation corresponding to the shadowgraph sequence shown in Figure 1. The grayscale colormap displays the density gradient with dark regions corresponding to maximum density gradient.