Final Report for
Assessment of the 1D Isentropic Flow Assumption in Characterizing the Flow in a Converging-Diverging Nozzle
Society of Physics Students 2012 Undergraduate Research Award

Summary:

This SPS project is part of Bethel University’s (BU) ongoing research that is assessing the validity of the isentropic flow assumption in the converging-diverging (CD) nozzle of the Bethel University (BU) supersonic blowdown tunnel. Piezoelectric pressure measurements and high-speed video (HSV) shadowgraph imaging are used to study and characterize the compressible flow and shock waves in the CD nozzle. Experimental data is gathered from the BU supersonic blowdown tunnel. SPS funds were used to manufacture Mach 3 and Mach 4 CD nozzles with geometries based on Method of Characteristics (MoC). Additionally, SPS funds were used to purchase a Kulite miniature pressure transducer for dynamic measurements of air pressure in the nozzles during tunnel operation.

The Bethel Physics Department places a strong emphasis on open-ended project and research-like experiences in its upper-level physics curriculum. Advanced lab projects are important components in several upper-level physics courses, including Fluid Mechanics, Optics, Contemporary Optics, and Computer Methods in Physics and Engineering. Several recent student projects have focused on applications involving compressible flows and shock waves [1-4]. In fall 2010, a student project in the Fluid Mechanics course was directed toward the design, construction, and initial testing of a small supersonic blowdown tunnel. Subsequent student research has included preliminary high-speed video shadowgraph imaging of the flow in
the converging-diverging nozzle and the development of a MATLAB program for comparison between experiments with the tunnel and simulations of the flow in the CD nozzle.

Preliminary preparations for this SPS project began in the spring of 2012 through an independent senior research project and a student project in *Computer Methods in Physics and Engineering*, an upper-level course in the BU Applied Physics program. The senior research project yielded a MATLAB program that modeled the blowdown in the CD nozzle based on the isentropic flow assumption and normal shock relations. Figure 2 shows the visual display of the MATLAB GUI and simulation results [2]. A LabVIEW VI (virtual interface) was also created in *Computer Methods* to take dynamic pressure measurements using two Kulite piezoelectric pressure transducers. These transducers would
eventually be machined into the wall of the CD nozzles to take transient pressure measurements at different streamwise positions throughout the tunnel blow down operation.

During the summer of 2012, the design for the CD nozzles was created using a FORTRAN code obtained from the Air Force. This code yielded designs for both a Mach 3.0 and Mach 4.0 CD nozzles. While the nozzles were being machined at a local machine shop, prototype nozzles were prepared to hold the pressure sensors. Aluminum sleeves are sealed into the acrylic face of the nozzle at regular intervals along the diverging section of the nozzle, and the pressure sensors are threaded into place inside the sleeves. The sleeves are threaded and glued into place flush with the inner wall of the nozzle to ensure a tight seal so lower pressures, on the order of 5-10 Torr, may be applied to the test section before tunnel operation. The aluminum sleeves were hand machined and glued into place carefully as to keep the acrylic face free from fingerprints and glue that would obstruct the light necessary for shadowgraph imaging. The acrylic wall of the nozzle remains flush with the sensors, since any protrusion by the sensors will result in standing shock waves during operation. Shadowgraph studies carried out with the instrumented models verified that the pressure sensors do not obstruct the flow and create standing shockwaves in the nozzle during a blow down. The LabVIEW interface was also modified during the summer to support two additional pressure sensors, ordered with department funds, and additional functions such as data analysis, processing, and export. The LabVIEW interface has customizable settings for

Figure 3: Mach CD nozzle instrumented for simultaneous pressure measurements at four stations along the diverging section of the nozzle.
sensor calibration, sample rate, and filter strength that allow all data to be processed and viewed in real time before being saved to a .csv file. Results were presented in a poster session at the 2012 Conference on Laboratory Instruction Beyond the First Year of College [4].

The final stage of the project was carried out in fall 2012 to collect data on the two new nozzles with shadowgraph imaging and pressure measurements. This work was supplemented by student project work in the BU Fluid Mechanics course. The resultant HSV from shadowgraph imaging was analyzed to determine if the MoC was an effective tool to design CD nozzles matching the isentropic assumption. The Mach 3.0 nozzle showed some improvement, characterized by a linear shock boundary towards the end of the diverging section of the nozzle. Figure 5 shows two frames from the HSV shadowgraph imaging during the blow down of the Mach 3.0 nozzle. Shadowgraph results for the Mach 4.0 nozzle were inconclusive and will require additional work. Operating
conditions for this nozzle result in very low pressures in the diverging nozzle sections, limiting
the effectiveness of our shadowgraph imaging. The lower densities in the Mach 4.0 diverging
nozzle result in much smaller refractive index variations. Future studies with higher driving
pressure conditions are expected to result in much more definitive HSV shadowgraph imaging
results.

Pressure data for the Mach 3.0 nozzle was measured using the LabVIEW interface. Data
were taken among all four pressure sensors simultaneously at 5000 samples per second in three
data sets. All three data sets may be seen in the appendix. A sharp peak can be seen on the
pressure reading for the sensor placed at the throat. The throat experiences massive compression
as air rushes through the nozzle, but the pressure never exceeds the operating pressure of the
tunnel for a Mach 3.0 nozzle, about 40 PSI absolute pressure. One might notice the negative
pressure readings that exist in all three graphs. This anomaly is seen in all three data sets on the
second pressure sensor in a consistent fashion. The source of this anomaly is not yet known,
although its consistency is encouraging for exploration. However, analysis of the pressure traces
clearly depict the receding shock wave during the tunnel blow down with timings that is
consistent with shadowgraph imaging and simulation data.

The BU supersonic blowdown tunnel is an ideal apparatus for student-led research in
compressible flows. Pressing on into the future, the nozzles and sensors that were purchased
using funds from this grant will be valuable in follow-on studies and other future student projects
at BU on compressible flows.

References:

shock waves,” Proceedings of the 2012 March meeting of the American Physical Society
March Meeting, (APS, Boston, 2012).


**Spending Summary:**

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<th>Date</th>
<th>Description</th>
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<td>Mach 3 nozzles (2)</td>
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<td>Cast Acrylic windows for nozzles</td>
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<td>6/11/12</td>
<td>Kulite Subminiature IS pressure transducer</td>
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<td>7/5/12</td>
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*Bethel University Physics Department internal funds supported the project through the purchase of 3 additional pressure transducers and miscellaneous supplies needed to carry out this project.*
Appendix: Pressure Sensor Data

Run 1:

Run 2:

Run 3: