Influence of Critical Length on Open-Shock Tube Experimentation

Connor S. Wilson

University of New South Wales at the Australian Defence Force Academy

Open shock tube experimentation is commonly used to investigate shock-vortex interactions and noise generation in compressible flows. It is claimed in the literature that the pressure pulse and subsequent flow induced by the incident shock of an open shock tube can be influenced by manipulation of the so-called critical length ratio. This is defined as the value of the ratio of the high pressure part length (HPL) and the low pressure part length (LPL) of the open-shock tube which allows for the expansion head and shock front to simultaneously arrive at the opening of the tube. This work experimentally investigates, mainly through flow visualisation, the influence of the high-pressure part length on the output flow from an open shock tube. Experiments were conducted at both above and below the critical length ratio for two shock Mach numbers. The results were processed to establish a baseline into the effects of the above and below critical length conditions. It was revealed that when operating below the critical length ratio, some features of the flow exiting the tube change and the outflow conditions vary with time. The conducted experiments quantify the amount of these variations.

Nomenclature

\[ P \] = Pressure
\[ \gamma \] = Ratio of specific heats
\[ M \] = Mach Number
\[ v \] = Velocity
\[ ts \] = Time for shock to exit tube
\[ tc \] = Time for expansion head to cross contact surface
\[ te \] = Time for expansion head to reach exit
\[ \Delta M \] = Uncertainty in Mach number
\[ CF \] = Comparability Factor
\[ CL \] = Critical Length

I. Introduction

The concept of critical length first appears in the literature in 1997 when Brouillette and Herbert published a study on the propagation of compressible vortex rings. The paper claims that by having an adjustable high pressure section length, they could vary the pressure pulse seen at the opening of the tube. The critical length ratio is defined by (Thangadurai & Das, 2010) as the length at which the head of the expansion fan that is reflected from the back wall of the shock tube just meets the incident shock at the opening of the tube. The existence of such a critical length gives rise to three flow regimes (Brouillette & Herbert, 1997).

The first regime exists when the driver length is larger than the critical length. In this case the shock, vortex ring and flow have all exited the tube well before the arrival of the expansion fan. This set-up is said to cause the jet to interact with the vortex ring and cause it to break up soon after formation. The influence of the trailing jet has been noted in several papers (Kontis, et al., 2006). The next flow regime occurs when the length ratios of...
the tube are at the critical value. In this condition the head of the expansion wave reaches the opening shock tube at the same time as the incident shock. This eliminates the jet flow trailing the vortex ring and prevents disturbance, allowing the vortex ring to propagate further downstream. The third regime exists when the driver length is shorter than the prescribed critical length and the expansion waves interact with the shock within the tube. Brouillette et al. (1997) claims this regime is similar to the second, only the pressure is reduced due to the expansion fan, however this similarity is not quantified.

The concept of critical length is yet to be experimentally investigated and has not been widely accepted in the open shock tube research field. Whilst some researchers, such as (Kontis, et al., 2008) attempt to operate at the so-called critical length ratio, others choose not to do so, e.g. (Kitajima, et al., 2009). The uncertainty in the influence of shock tube length ratios is a gap in fundamental understanding that may have a significant influence on experimental results investigating output flow such as vortex rings. This paper aims to ascertain how the critical length ratio influences the output flow of an open shock tube and in doing so evaluate how experimentally feasible it is to operate at the critical length ratio.

II. Background

An open shock tube is an apparatus that is used to generate supersonic flows that are then free to interact with the ambient air. The flow within the tube can be broken into three primary features, the shock wave, the contact surface and the rarefaction fan. The shock wave is generated by the large pressure differential which is experienced in a small time frame, in the case of the open shock tube; the bursting of the diaphragm provides these conditions. Figure 1 below is an x-t diagram illustrates the flow features within an open shock tube for operation at the critical length ratio.

The shock wave travels through the ambient air in the low pressure length toward the open end of the tube, dragging with it the fluid in the tube. This shock wave travels at a constant speed \( M_1 \), which is relative to the pressure ratio across the diaphragm, which his illustrated by the equation below. It is worth noting that regions 1 and 4 are both air, therefore the equation simplifies.

\[
\frac{P_2}{P_1} = \frac{2\gamma_1 M_1^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \left(1 - \frac{\gamma_4 - 1}{\gamma_4 - 1} \left(M_4 - \frac{1}{M_4}\right)^{\gamma_4 - 1}\right) \]  

(Gaydon & Hurle, 1963)

Behind the shock wave travels the contact surface, this is defined as the boundary between the driver gas and the shocked gas. The contact surface also travels with a constant velocity, \( v_2 \), towards the open end of the tube and the velocity of the flow on either side of the contact surface is equal. The rarefaction fan is the rapid expansion of the pressurised driver gas. This expansion fan is a series of waves that travel with diminishing speeds. For simplicity the rarefaction wave can be broken into two features; the expansion head and the expansion tail. The expansion head travels towards the closed end of the tube with a velocity equal to the local speed of sound as the fluid is stationary. The expansion tail travels with velocity equal to the difference between the local particle velocity and the local speed of sound. When the flow within the shock tube is subsonic, the expansion tail will travel towards the back wall upon the bursting of the diaphragm. When the flow in the shock tube is supersonic, the expansion tail will travel towards the open end of the tube when the diaphragm is burst.

In order to reach the opening of the shock tube, the expansion head must first cross the remainder of the expansion wave and afterwards the contact surface. The expansion head accelerates through the expanded gas due to increasing particle speed. Once the expansion head crosses the expansion tail, it is travelling towards the open end of the tube at velocity equal to the sum of local speed of sound and particle velocity, \( v_3 + a_3 \). When the expansion head crosses the contact surface it accelerates to velocity \( v_2+ a_2 \), this is due to the increased speed of sound in the shocked gas that exists between the shock front and the contact surface. Therefore as the expansion head travels through the shocked gas it is reducing the pressure in the shocked gas, which explains why the flow features trailing the shock front are influenced, resulting in features like a reduced velocity of the vortex ring. However, as long as the reflected expansion head does not catch up with the shock front, this front remains un-influenced. If the experiment is run at the critical length ratio, the expansion head will meet the shock front at the opening of the tube. Figures 2 and 3 illustrate the same process for conditions at, below and above the critical length ratio, respectively.
Figure 1. X-t Diagram of open shock tube for Critical Length. Interactions between rarefaction/expansion head with tail and contact surface are illustrated along with velocity change (Gaydon & Hurle, 1963).

Figure 2. X-t Diagram of open shock tube for a condition below Critical Length.

Figure 3. X-t Diagram of open shock tube for a condition above Critical Length.
III. Experimental Set-up/ Testing Method

A. Apparatus

The experiments conducted within this paper were conducted with a cylindrical open shock tube with 20 mm inner diameter. The tube has two primary sections, a high pressure length (HPL) section and a low pressure length section (LPL). This LPL section is open to ambient air and features two pressure transducers close to the exit. These pressure transducers are located 60mm apart with the second transducer being 50mm from the opening of the tube. The transducers are Kistler piezoelectric pressure sensors which are better suited to detecting highly dynamic pressure readings such as shock waves when compared to piezo-resistive transducers because they have a lower response time and a lower tendency to “ringing” (Kistler Holding, 2016). The pressure transducers are connected to an oscilloscope which saves the data recorded by the transducers. The HPL section is formed of a plunger section and other pipe sections of various lengths. These sections are selected to produce a desired HPL. Table 1 shows the various HPL sections used during the conduct of experiments and the critical length condition each HPL induced. The two main tube sections are divided by a diaphragm, which typically is a number of overlain plastic discs of thickness 12µm. The tube itself is mounted on a horizontal frame and pressurised air is fed through the end flange of the high-pressure part, where the pressure is displayed on a gauge. The pressure hose then passes through a valve and then connects to the sealed HPL section. The imaging set-up consisted of a standard Z-schlieren imaging system with a high-speed camera (Shimadzu HPV-X), which is typically operated at frame rates of 100,000 or 200,000 frames per second (fps). The camera records 128 frames with a resolution of 400 x 250 pixels.

<table>
<thead>
<tr>
<th>Operating Mach</th>
<th>HPL Length (m)</th>
<th>Critical Length Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.45</td>
<td>0.172</td>
<td>above</td>
</tr>
<tr>
<td>1.3 &amp; 1.45</td>
<td>0.472</td>
<td>above</td>
</tr>
<tr>
<td>1.3</td>
<td>0.122</td>
<td>above</td>
</tr>
<tr>
<td>1.3 &amp; 1.45</td>
<td>0.1</td>
<td>below</td>
</tr>
</tbody>
</table>

Table 1. High Pressure Length sections used throughout Testing

B. Process

Prior to conducting a testing phase, the apparatus and imaging system were calibrated. Firstly the schlieren image was calibrated using a calibration lens to ensure that the schlieren cutoff was properly positioned and that lighting was sufficient to visualise the flow. After confirming that the set-up was operational and complete, the testing phase would begin. For each individual test the process was to separate the HPL section from the LPL section, insert the diaphragm and reconnect the sections. Next the pressure transducers, oscilloscope, delay unit and camera were armed. Then the HPL section was pressurised to the desired pressure for that test. The valve to the HPL section would then be closed to ensure that the gas volume in the high pressure part is constant for each run. Once ready, the plunger was activated, penetrating the diaphragm and allowing the shock wave to form and eventually exit the open shock tube. The passing of the shock over the transducers triggered the recording process and the data were recorded.

C. Testing Matrix

The calculation of the critical length ratio relied heavily on analytical relationships (Gaydon & Hurle, 1963). The MATLAB code developed to predict the critical length required some parameters of the shock tube and ambient gas to be selected. The LPL of the tube was fixed and the operating medium was considered sea level air. For a single Mach number, the code used the stipulated conditions and calculated the time taken for the shock front and expansion head to reach the opening of the tube. The code then iterated solutions for the HPL until the time for both features to reach the tube exit was the same. This could be repeated for a range of Mach numbers and therefore provide a plot to show how HPL varies with Mach number at a fixed LPL. This plot is shown below in Fig 4.
Early development in the code assumed that the flow within the shock tube was supersonic for all Mach numbers. This assumption influences the velocity of the expansion tail as the tail travels with velocity relative to the difference in local particle velocity and local speed of sound. The transition from subsonic to supersonic flow within the shock tube occurs at approximately Mach 1.6. This gives rise to the two trends seen in Fig. 4. The results from this MATLAB script were used to design the testing matrix for this paper. In the tests conducted here, the shock-induced flow in the shock tube is always subsonic, so that only the left portion of the curve seen in Fig. 4 is relevant.

The test matrix was designed to provide results that would answer the research questions of this paper, whilst incorporating the constraints of the UNSW test facility. The tests were run with two Mach numbers, 1.45 and 1.3. These values were chosen based on the pressure available for the tube and the given diaphragm thicknesses. Mach 1.45 was the highest available Mach number with the supplied pressure, the value of M1.3 was chosen as it falls below both disputed criteria for the formation of a rearward facing shock within the vortex ring. The two length conditions for each Mach number are below and above critical length.

The length ratios selected for each test were done so based on the previously developed code that estimated the critical length ratio. It was deemed that it is unpractical to attempt an experiment at the exact critical length due to uncertainties in the model along with limitations of the laboratory equipment. Therefore experiments were conducted at above and below the critical length. The quantification of how far below/above the test was conducted is defined later in this paper. For both Mach numbers tested, the LPL section remained constant at 1.635m, this was done both to maintain consistency and because the model used to predict the critical length showed the HPL had a larger variation for a longer LPL, this allows for a greater range of configurations to be selected.

### IV. Uncertainty Analysis

This section describes both the systematic and the random uncertainty associated with the experiment technique and apparatus. For each test, the desired output was a recording of the Mach number. This was achieved in two ways: firstly the time taken for the shock to travel between the two pressure transducers was recorded and this was used to calculate a shock velocity. The local temperature was then recorded using two thermometers and this was used to calculate a shock Mach number. The second method involved using the schlieren images to estimate the Mach number; this was done using the known time between frames and measuring the shocks change in location via pixel count. Both methods included uncertainties which will be discussed below.

The first method of measuring Mach number, as mentioned above, utilised the testing equipment to estimate the velocity of the shock front. This method induced two primary sources of uncertainty, the recording of the temperature and the time difference between the shock front passing over each pressure transducer.
A. Measuring the Temperature

The entirety of the testing phase was conducted within the ADFA Supersonics Laboratory, which is a heated lab. When conducting the experiments, the local temperature was measured using an electronic thermometer which was located approximately 1m from where the open-shock tube was situated. This thermometer was used to record the local temperature immediately after every test conducted. There was also a second mercury thermometer which was situated approximately 2m away from the shock tube. The temperature reading directly affects the local speed of sound calculations and therefore the Mach number estimations for each test. The uncertainty of the temperature reading is caused by the varying temperature gradients within the laboratory. With the heating system being overhead of the experiment set-up, there is no guarantee the temperature within the shock tube is exactly the same as the electronic thermometer reading. The uncertainty for the temperature measurements is ±0.5K. This figure has been selected conservatively as it is difficult to quantify the uncertainty within the measurements. The uncertainty in the Temperature measurement will influence the local speed of sound calculation and therefore the calculated Mach number.

B. Measuring the Time Difference

The velocity of the shock front was measured using a simple distance over time equation. The distance was fixed throughout the testing scheme. The distance used is the distance between the two pressure transducers that are embedded within the tube. The two pressure transducers are 60mm apart. The time taken for the shock to travel across both pressure transducers was measured from the pressure readings displayed in the oscilloscope. When the shock front passes over the surface of the pressure transducer, the pressure is not exerted instantaneously; rather the pressure is exerted gradually over a very short time frame, this can be seen later in Figs 9 & 10. This yields readings that closely match a linear increase in pressure until reaching equilibrium; therefore the shock front location is uncertain. In order to measure the time taken for the shock front to traverse the distance between the two transducers, the shock front was taken to be halfway along the pressure jump. This middle point was found by taking one half of the pressure after the arrival of the shock and adding the baseline pressure reading prior to the arrival of the shock.

The scale used on the oscilloscope had time steps of 0.05µs and therefore the uncertainty in selecting the point which has been identified as the middle is at least ±0.1µs. The selection of the mid-point itself also has an induced uncertainty which is more difficult to quantify, therefore a conservative value of ±0.1µs is assigned. This brings the total uncertainty in estimating the time for a single pressure transducer to ±0.2µs. This figure is justified as there is uncertainty in calculating the point at which the shock front arrives and uncertainty in selecting the correct time due to the timestep increments of the oscilloscope. When this uncertainty is compounded for both pressure transducer readings using the equation below, it gives a total uncertainty of ±0.6µs.

\[ \Delta t = \sqrt{\Delta t_2^2 - \Delta t_1^2} \]

C. Mach Uncertainty

The total uncertainty associated with the Mach reading varied for each test, however this uncertainty analysis allowed for a baseline for Mach comparability to be established. Due to the nature of shock tube testing, it is extremely difficult to conduct experiments at the exact same Mach number. This uncertainty analysis has shown which test Mach numbers lie within the same uncertainty margin. Tests which satisfy this criterion can confidently be assumed to have the same Mach number. This is exemplified in Fig. 5 below, which shows the calculated Mach number for a sample of experiments along with the uncertainty induced through the measurement method. In order to quantify exactly how comparable the Mach number of two tests were, the ‘Comparability Factor’ was developed. This factor is defined as the difference in the Mach number reading for each experiment divided by the uncertainty in the readings.

\[ CF = \frac{|M_2 - M_1|}{\Delta M} \]

When \( CF < 1 \) the two tests can be considered comparable and when \( CF > 1 \) the two tests are non-comparable. These brackets for the Comparability Factor (CF) are selected based upon the results from the testing phase of this paper. It will later be shown that as the CF exceeds a value of 1, the physical output flow of the experiments will differ.

D. Schlieren Image Mach Calculations

The second method of measuring the Mach number utilised the first few frames from the schlieren imaging to estimate the shock front velocity. For each testing phase, a calibration run was conducted. This testing run involved recording schlieren images of a calibration lens. The dimensions of this lens are known and can be used to generate a scale for the images which converts pixels to a unit length of millimeters. In tests that showed
a moving shock wave, the time difference between frames is known and therefore the shock front velocity can be estimated. Figure 5 below shows the uncertainty for the Mach number estimations for both methods. It is clear that measuring the shock velocity using pressure transducers is far more accurate than using the schlieren images. This is due to the large field of view used in the testing process, which reduces the spatial resolution of the recording. The experiments were not designed to measure Mach using images rather aimed to capture the flow features exiting the tube. The results provided from the Mach estimate using the schlieren images are in agreement with the pressure transducer readings, however to reduce the uncertainty the field of view of the camera would need to be reduced.

![Mach Number and Uncertainty for two measurement methods.](image)

This section has discussed, in detail, the methods in which the experimental Mach number for each test run was calculated and the associated uncertainty with each method. This data has been used to establish a baseline on the comparability of test Mach numbers. In order to investigate the influence of critical length, it was necessary to first establish what tests can be considered comparable with regards to the shock Mach number. This allows for future comparison of tests at comparable Mach number but at different length ratios as the Mach number influence has been quantified.

V. Results

In order to answer the research questions, the raw data from the testing phase was processed to first deliver a baseline of how Mach number influenced the flow. Once this was achieved, the results could then be compared for both above and below critical length conditions at comparable Mach numbers.

Firstly the TIFF schlieren images for each experiment were converted into X-t diagrams. The images for each test were sorted to ensure the shock had exited the tube prior to constructing the X-t diagrams. The diagrams were constructed using a specifically designed Matlab script. This code would stack the centre row of pixels for each image obtained in one experiment. The first image would form the bottom row; the second image would form the second row and so on until reaching the final image. The resultant X-t diagram would show the trajectories of the flow features and allows for direct qualitative comparison. The most effective way to compare the differences in these X-t diagrams was to merge two individual diagrams into a single plot. This was achieved by setting one of the diagrams to 50% transparency and then overlaying the two plots.

This method was used to first establish a baseline on the influence of Comparability Factor on the output of the flow. Figure 6 below shows the X-t diagram overlay for two tests which have a CF value of less than 1, it is evident in the overlay that there are no discernible differences between the two X-t diagrams. Figure 7 shows an X-t diagram overlay for two test runs with a CF that exceed the comparable threshold by a factor of 2. It can be seen in this overlay that the Mach number variation directly influences the trajectory of the output features. Now that the influence of Mach number on the output features has been established, the influence of Critical Length can be quantified. Figure 8 contains the X-t diagrams for two tests with a CF value less than 1, however the two tests operate at different critical length conditions, one operates at below the critical length and the other above. The overlay of these two X-t diagrams shows that operating length ratio has a clear influence on the flow features, specifically the vortex ring, this is shown by the diverging trajectories. When operating below the critical length ratio, the expansion head reduces the pressure of the shocked gas as it approaches the shock front,
therefore it is expected that the flow features trailing the shock front are slowed. Figure 8 also shows that towards the end of the test time, the shock front trajectories also begin to deviate. As the tests are being operated 5% below the critical length it is reasonable that the shock’s trajectory is not heavily influenced by the expansion head.

The experiments also provided pressure readings for the two pressure transducers within the tube. The pressure readings for each transducer can be plotted to give a pressure reading for the duration of the experiment. Figure 9 and 10 below are plots of the pressure readings for experiments conducted above and below the critical length ratio. In both plots the arrival of the shock front is clearly illustrated with a jump in pressure, reading slightly below 0.8bar. It is noted that there is a slight disturbance with the arrival of the shock, which is caused by the pressure transducer disrupting the flow and is unavoidable with the given test equipment. When the shock exits the tube, an expansion fan is generated and travels backwards from the opening of the tube. This is first observed in the transducer closest to the opening, transducer 2. Fig 9 illustrates a constant pressure reading after the arrival of the shock front, until the pressure is reduced from the expansion wave heading upstream from the open-end of the tube. These results are consistent with expectations when operating at the above critical length condition. Fig 10 however shows a constantly decaying pressure at all times after the arrival of the shock when operating below the critical length condition. This decay is caused by the expansion head. The expansion head has passed over the contact surface and begun to reduce the pressure in the shocked gas. The degree to which the expansion reduces the pressure of the shocked gas can be quantified by finding the difference between the two pressure readings for the above and below conditions at comparable Mach numbers. Figure 11 shows the pressure reduction caused by the expansion head when operating at below critical length. This plot shows that for 0.4ms of exposure to the expansion head, the gauge pressure has dropped by over 20%. This would cause the flow features to exit the tube at varying effective pressures.

Above CL at CF 0.14

Test 32 18% Above CL X-t  
Test 33 18% Above CL X-t

Overlay

Figure 6. X-t Diagram overlay for Comparable Mach numbers.
Above CL at CF 2.02

Figure 7. X-t Diagram overlay for Non-Comparable Mach numbers.

Above vs Below Critical Length for CF=0.01

Figure 8. X-t Diagram overlay for Above Critical Length Condition and Below Critical Length Condition at comparable Mach numbers.
Figure 9. Gauge Pressure Reading for Above Critical Length

Figure 10. Gauge Pressure Reading for Below Critical Length

Figure 11. Gauge Pressure Reduction. The difference in pressure reading for comparable tests operated at above and below critical length condition. Pressure is taken from the first transducer

VI. Summary of Results

The testing matrix for this investigation consisted of over 40 open shock-tube experiments. The results for these experiments have been summarized above. This section will deliver the findings on the influence of the critical length ratio of open-shock tube flow.

The x-t diagrams were used to qualitatively compare the output flow for three operating conditions; comparable Mach numbers at the same length ratio condition (Fig. 6), non-comparable Mach numbers at the same length ratio condition (Fig. 7) and comparable Mach numbers at different length ratio conditions (Fig 8). The first two operating conditions confirmed that the output flow of two tests operating with a comparability factor of value less than 1 are visually indistinguishable, whereas if the comparability factor exceeded 1, the results began to visibly diverge. Figure 8 depicts the previously described operating condition when two tests at comparable Mach were overlain to contrast the output flow differences when operating at the two different length ratios; below and above critical length. This image shows the flow features trailing the shock front are the most heavily influenced with a slowed trajectory, however shock attenuation becomes more distinguishable in the later frames of the images. It was discovered that when operating at the below critical length condition, the pressure ratio across the diaphragm needed to be increased to prevent excessive shock attenuation and achieve resultant Mach numbers equal to those when operating at the above critical length condition. This confirms that when operating below the critical length ratio, the flow features will exit the tube at a lower pressure than that of a flow generated by a length ratio that is well above the critical length ratio. This is due to the pressure reduction caused by the reflected expansion head.
The pressure readings for each experiment granted further insight into the process occurring within the shock tube. Figure 9 confirmed expectations that when operating at over 300% above the critical length ratio, the expansion head does not influence the output flow. This is because the HPL is suitably long that the expansion head fails to cross the contact surface before the shocked flow has exited the tube. When operating slightly above the critical length ratio, such as 18% above, the expansion head crosses the contact surface and slows the trajectory of the flow features trailing the shock. Figure 10 shows that when operating below the critical length ratio, the pressure is continuously being decayed by the arrival of the expansion, the pressure readings for a test operated slightly above the critical length ratio yield similar results. The effect of the expansion head on the pressure within the shocked flow is quantified in Fig. 11. The degree to which the expansion influences the shocked flow varies across the compared tests. This is because replicating the results from a single test is extremely difficult in shock tube testing as miniscule variances in temperature, diaphragm properties and pressure can strongly influence the output. This also makes the time and location at which the expansion head crosses the contact surface and reaches the shock front difficult to determine. A possible solution that has been implemented by (Kontis, et al., 2008) involved mounting a pressure transducer at the opening of the tube, however as seen in the pressure readings in Fig 9 & 10 it is near impossible to determine exactly where the expansion head begins to influence the flow. It is due to the uncertainties involved in predicting the critical length, repeating the exact conditions for a single flow condition and identifying if critical length was experimentally achieved that the operating at critical length for a test matrix is unfeasible.

In their 1997 paper investigating vortex rings, Brouillette and Herbert claimed that when operating above the critical length condition that a jet structure would push through the vortex rings and cause them to break up. This was not observed during the conduct of experiments for this paper. Figure 8 shows the flow features, when operating above the critical length condition, are visible for equal time with a faster trajectory. When operating below the critical length condition or slightly above, the expansion head reduces the pressure in the shocked flow. The degree to which the expansion decays the flow is difficult to predict and varies for each experiment due to previously discussed variables. When operating well above the critical length ratio, which for this paper was 300% above the calculated critical length ratio, the expansion does not influence the pressure and the output flow between tests is of greater consistency.

VII. Conclusion

Literature claims that in order to achieve constant flow characteristics within the shock tube and therefore in the output flow, the length ratios must be set to allow the expansion head to meet the incident shock at the tube opening. Whilst in theory this is correct, if operating at the critical length the pressure of the flow should be reduced to the same degree for any given Mach number, this paper has shown that in practice, the critical length is not feasible. The findings derived from the experiment results suggest that if an operator wishes to remove the variable induced by the reflected expansion, it is more feasible to operate well above the critical length.

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References

[Accessed 11 September 2016].