MCEN 4228
Group Assignment 3
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Supersonic Nozzle Flow of a Rocket

The Purpose of the image is to visualize the flow near conical nozzle of the rocket motor. The whole idea is to observe the characteristics of the flow such as flow speed right at the nozzle exit, propagation of mach waves based on combustion chamber pressure change.

The apparatus for this images are hybrid rocket motor, nitrous oxide, steel I-beam based test stand, phantom v7.1 high speed camera, and pressure transducers. The set up of the apparatus is described below Figure 1. Pressure transducers are placed on the top of the combustion chamber and other feed lines. In this assignment, those placement is not going to be discussed. The rocket motor is built by Hwapyong Ko and 9 other seniors in aerospace department for their senior project. The fuel is HTPB(Hydroxyl Terminated Poly Butadiene) and the flame is generated burning with nitrous oxide. The 45 degrees angle convergent inner and 15 degrees angle divergent outer conical nozzle is built out of graphite and it was design to have sonic flow at the throat (Mach = 1) and supersonic at the exit of the nozzle (Approximately Mach ~ 3). The Reynolds number expected at the exit of the nozzle is ~10^{10}. It is very high Reynolds number due to the supersonic flow in a small flow diameter. The nozzle was design to have perfect expansion which means atmospheric pressure(Pa) and the exit pressure(Pe) are to be the same. However, the actual expectation of the

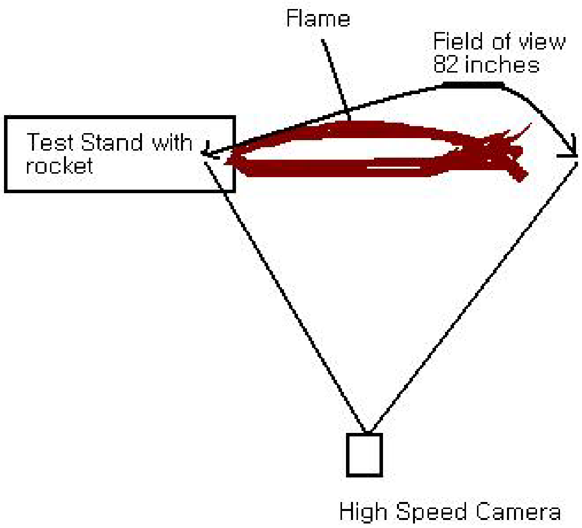

Figure 1: Apparatus Setup

observation is to see how exit pressure changes as combustion process goes. The observation was made based on the mach wave deflection angle at the exit of the nozzle. The red dashed lines in Figure 2 are the trace of the shock wave right at the end of the nozzle. The image was cropped about 7 inches in width of field of view.

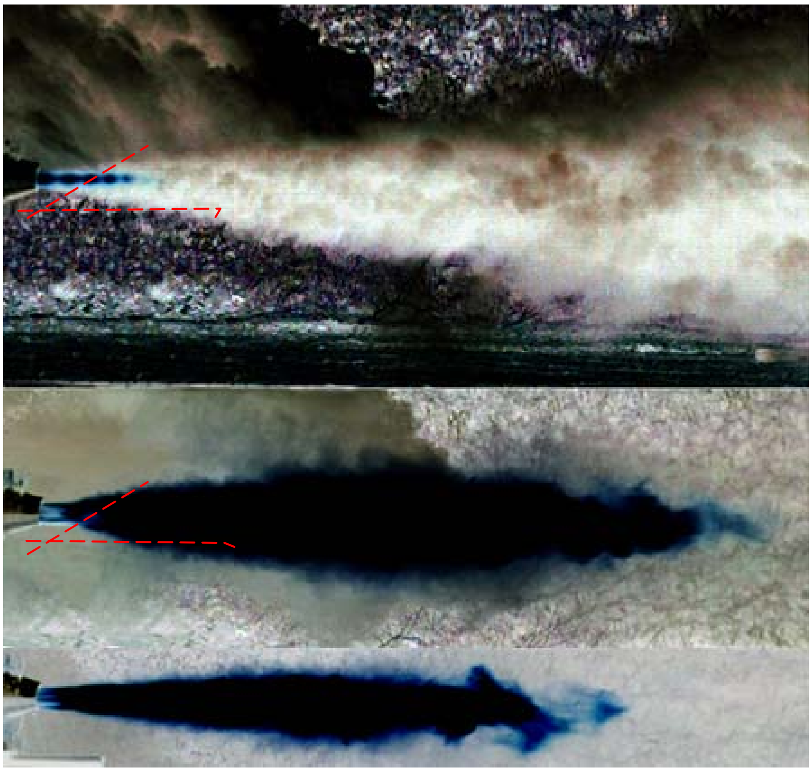

Figure 2: Shock waves at the Nozzle

Shock wave deflection angle tells the Mach number at the exit of the nozzle. The basic concept of shock wave is shown in Figure 3.

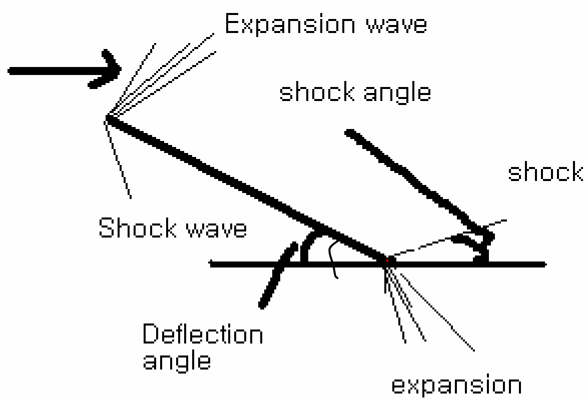

Figure 3: Shock wave in Supersonic Flow Region

The shape of the nozzle is similar to this model and the measured deflection angle is 15 degrees. Based on the observation from Figure 2, the shock angle is about 30~32 degrees. The Mach number was found based on shock wave diagram[1]. The Mach number is about 3 as expected theoretical calculation. Figure 3 is the diagram how the Mach number was determined.

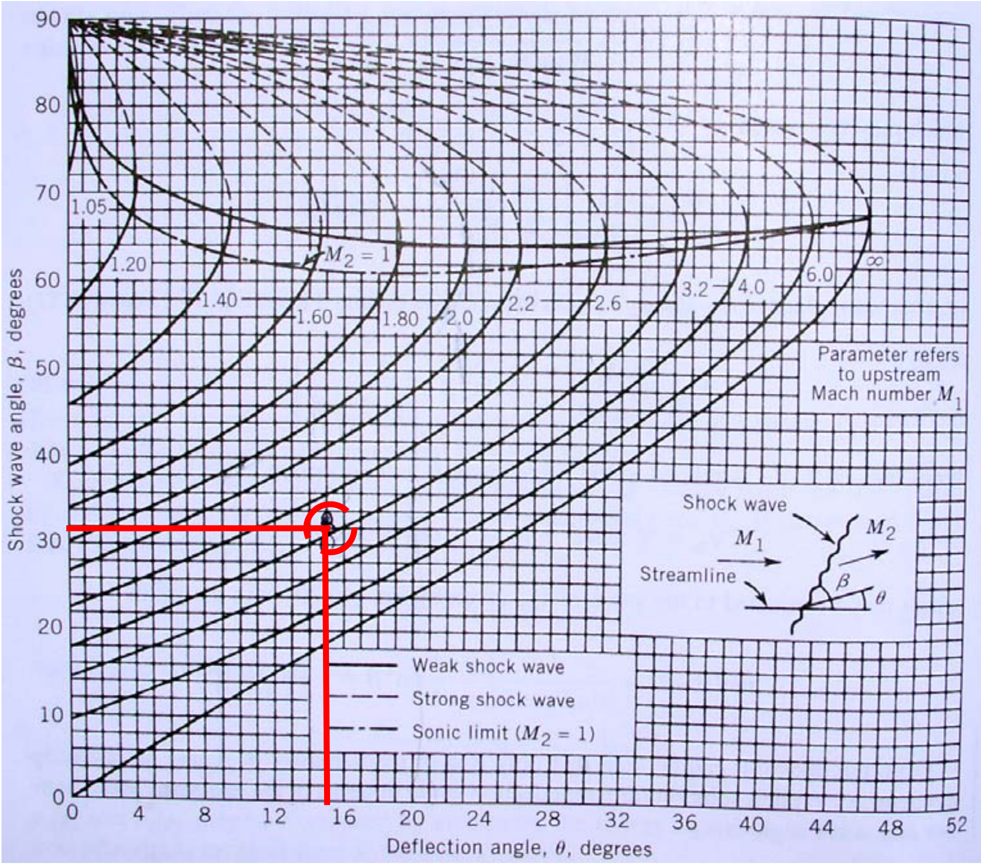

Figure 4: Shock wave Diagram

The second observation is shock wave form change over the combustion process. Figure 2 shows how the shock wave form changed over time. The images were listed starting from the top; beginning of the burn, middle, and ~11 second of the burn. The rocket total burn time was ~15 seconds. The nozzle performance can be described as function of nozzle pressure ratio and the nozzle expansion ratio. The nozzle pressure ratio was calculated based on the pressure data that was taken during the hot fire testing. The nozzle pressure ration ranged from 17.4 to 6.67. The nozzle expansion ratio is 6.23. The expansion ratio is the ratio of the nozzle exit area to the throat area. Figure 5 is how the shock wave and the pressure changed over time. It is indicated as dotted arrow. First two image in Figure to is more like dotted circle on the right in Figure 5. and the near end of the burn is similar to the dotted circle on the left. This is caused by pressure drop in the combustion chamber of the burn time. One of the reason combustion chamber pressure drop is due to decrease of mass flow rate of the oxidizer and the fuel regression rate. It can be proven visually in Figure 2. The length of the flame is getting short as time of the burn increases.

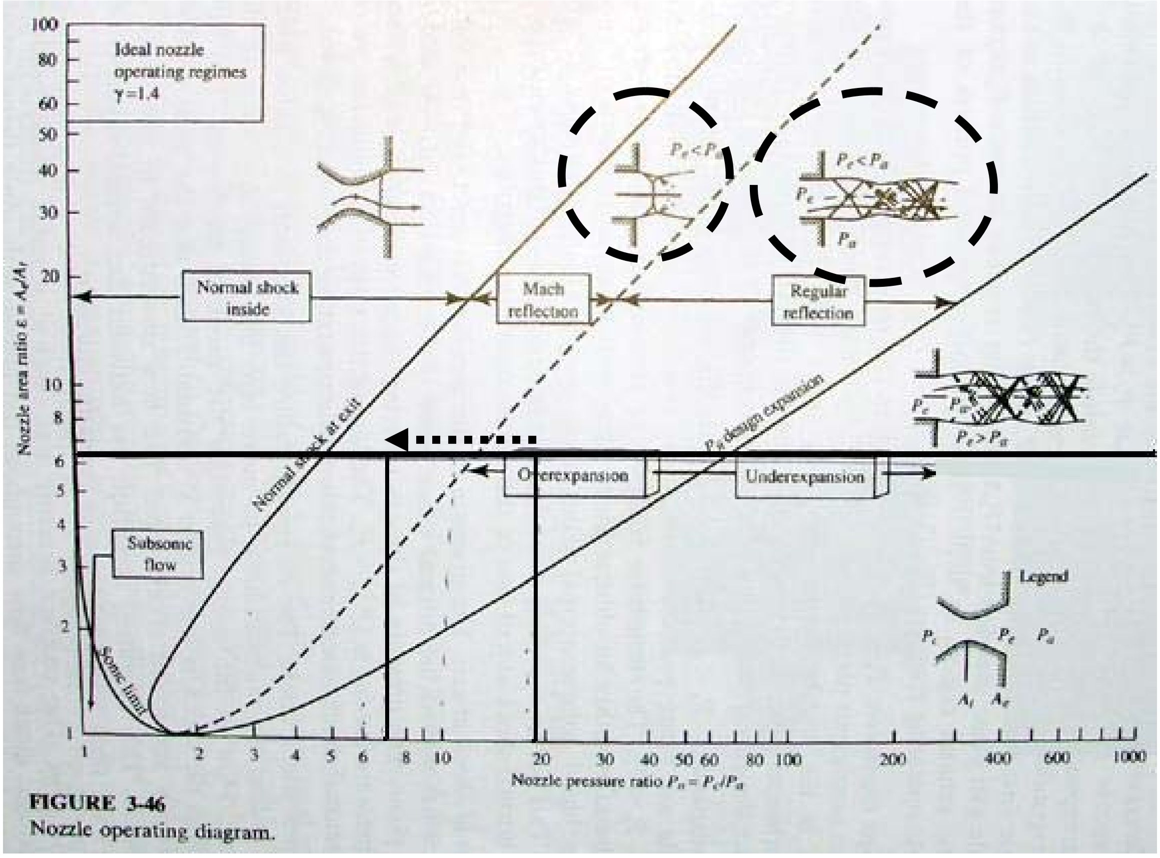

Figure 5: Nozzle Operating Diagram[2]

There is no special flow visualization technique used on the movie. Due to the limitation of information from Lockheed Martin, the high-speed camera information was only given exposure time and the resolution.

Camera	Phantom v7.1
Shutter Speed	1/200s
Resolution	800x600
Distance from object to lens	15 ft

The image in Figure 2 is just color inverted in photo shop.

The rocket performance wise the nozzle performed less than the expectation. It was started overexpansion condition due to the low chamber pressure. The image showed enough information how the nozzle performed. It would have been better if a proper filter was used for the high-speed image taking. The filter will show more information about the shock wave forming inside of the flame.

References

[1] Arnold M. Kuethe, Chuen-Yen Chow, Foundations of Aerodynamics 5th Ed. ISBN 0-417-12919-4
[2] Jack d. Mattingly, Elements of Gas Turbine Propulsion ISBN 1-156347-778-5