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CFD Analysis of Supersonic Exhaust Diffuser System for Higher Altitude Simulation

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ABSTRACT

A high altitude test facility of liquid rocket engine makes use of diffuser systems to evaluate the performance of the high expansion nozzle of the liquid engine. The low pressure environment of the operating rocket motor is simulated at ground level with the help of diffuser and also to recover the pressure of the exhaust gases before letting out to the atmosphere at ground level. The basic function of the diffuser is pressure recovery and sustaining the vacuum condition inside the test chamber. When the diffuser attains "started" condition, the momentum of the rocket motor exhaust creates sufficient suction to maintain low vacuum level in the test chamber and also the shock cells occurring in the diffuser duct seal the vacuum environment against backflow. The starting condition of the diffuser itself depends on the operational and geometric parameters of the diffuser and motor. Here a straight diffuser with a conical nozzle-area ratio numerically simulated by solving compressible Navier-Stokes equations for different back pressures. Mach contours are obtained for various operating conditions.

I. INTRODUCTION

Diffusers are deployed in various fluid systems like aircrafts, ramjets, scramjets, wind tunnels, gas turbines etc. They are also deployed in special applications like a high altitude test facility where the rocket engines are to be tested in low pressure environment where these engines are going to be put into operation. This low pressure environment has to be created at ground level and a suitably designed diffuser. The main function of the diffuser is to recover the low pressure of the exhaust gases to that of the atmospheric pressure. A diffuser maintains the required vacuum for testing the motor, by arresting back flow from the atmosphere into the test chamber using the momentum of the rocket exhaust. During the initial period, a part of the rocket exhaust plume may enter into the initially evacuated test chamber and thereby resulting in an increase of nozzle exit pressure. At high back pressure, the exhaust plume may separate in the nozzle divergent portion and consequently, the full thrust of the rocket motor will not be realized. In order to operate the rocket motor without any flow separation, the low pressure environment corresponding to the flight situation has to be created initially and maintained during the testing, with the help of an external diffuser device initially and after the achievement of supersonic flow at the diffuser inlet (known as the "diffuser started" condition).

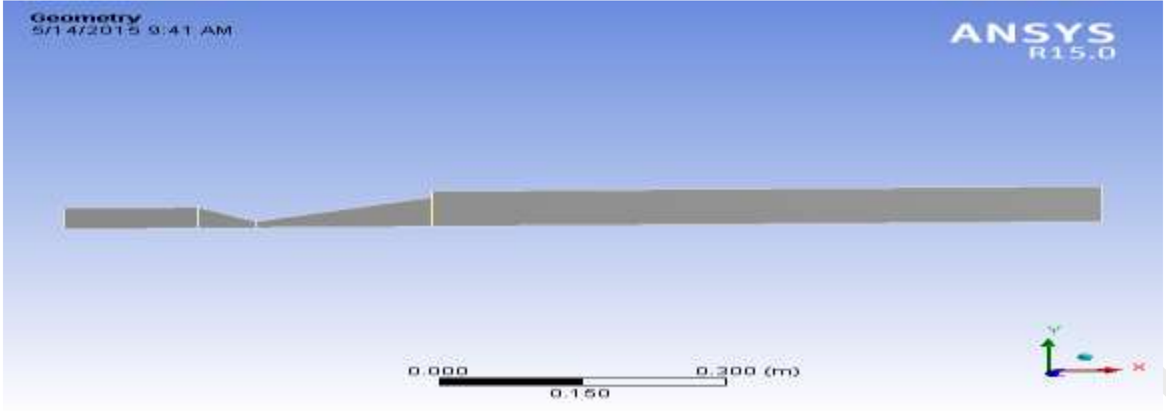

Fig.1 CFD model of supersonic exhaust diffuser with conical nozzle for higher altitude simulation

II. CONICAL NOZZLE

A conical nozzle of rocket engine is a propelling nozzle (usually of the de Laval type) used in a rocket engine to expand and accelerate the combustion gases produced by burning propellants so that the exhaust gases exit the nozzle at supersonic velocities. For nozzles that are used in vacuum or at very high altitude

III. SUPERSONIC EXHAUST DIFFUSER

A supersonic exhaust diffuser is the mechanical device that is designed to control the characteristics of a fluid at the entrance to a thermodynamic open system. Diffusers are used to slow the fluid's velocity and to enhance its mixing into the surrounding fluid. In contrast, a nozzle is often intended to increase the discharge velocity particular direction.

IV.COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics is a branch of fluid that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high speed supercomputers, better solutions can be achieved.

V. COMPUTATIONAL METHODOLOGY

1. Modeling of supersonic exhaust diffuser with conical nozzle

Supersonic exhaust diffuser system with conical nozzle is model by using the ansys fluent design modeler. The geometry was a two dimensional model (2D). The modeling parameters for supersonic exhaust diffuser system with conical nozzle are given below

Convergent angle of conical nozzle	30°
Throat Diameter of conical nozzle D*	0.03 m
Exit Diameter is D⍰	0.14 m
Area ratio of exit-to –throat of nozzle A⍰/A*	21.77
Divergent angle of conical nozzle	16.77°
Length/Diameter ratio of Supersonic Exhaust Diffuser	5m, 10 m
Length of the supersonic Exhaust diffuser	0.7m, 1.4m
Length of the Divergence part of nozzle	0.185 m

Table.1 Geometry parameters of supersonic exhaust diffuser with conical nozzle

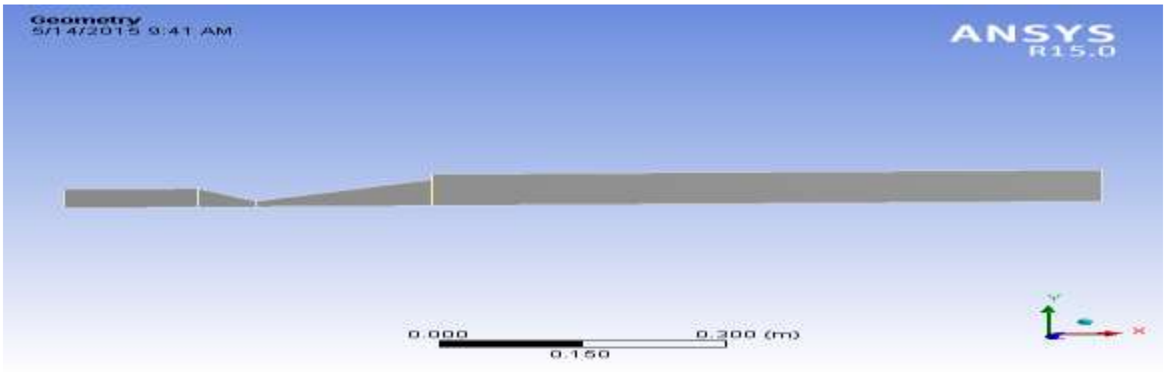

Fig.2 model for supersonic exhaust diffuser of length 0.7m with conical nozzle

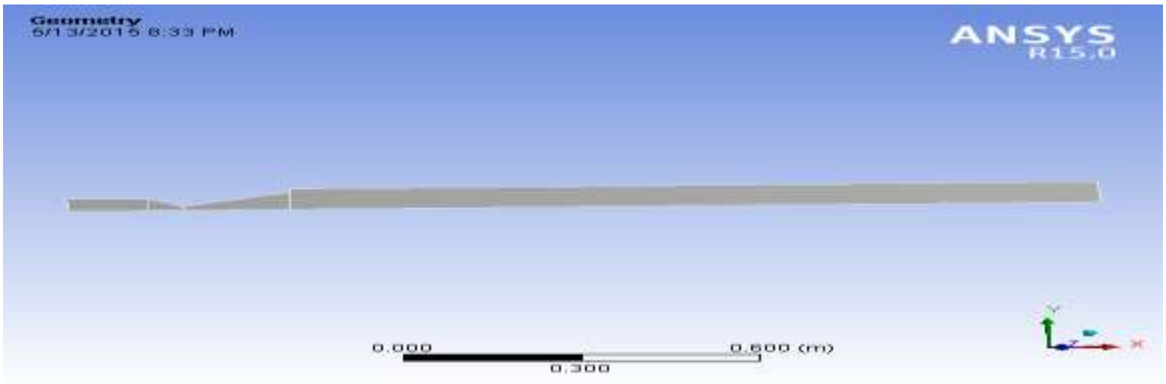

Fig.3 model for supersonic exhaust diffuser of length 1.4 m with conical nozzle

2. Meshing of supersonic exhaust diffuser with conical nozzle

Ansys icem cfd from the ansys fluent was used to mesh the model of supersonic exhaust diffuser with conical nozzle for the above diffuser length. For both the model the element size was 0.001 meters and quadrilateral elements are used. The mesh was fully structured mesh

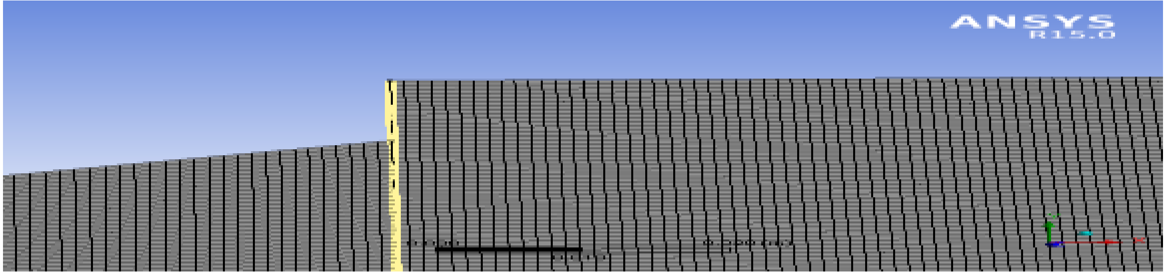

Fig.4 Mesh model for supersonic exhaust diffuser of length 0.7m with conical nozzle

Number of nodes: 83901

Number of elements: 82758

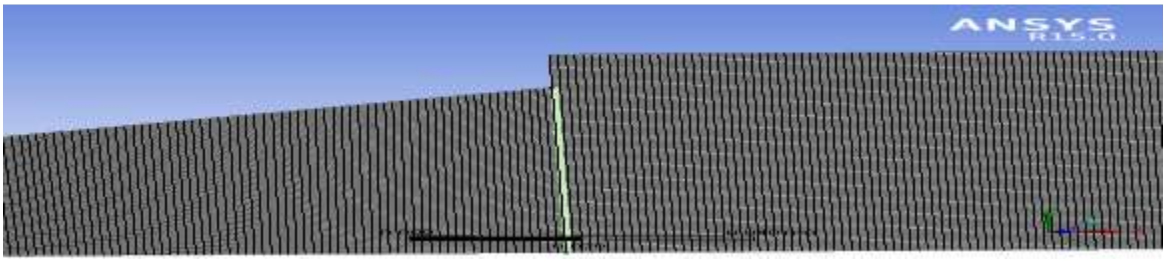

Fig.5 Mesh model for supersonic exhaust diffuser of length 1.4 m with conical nozzle

Number of nodes: 142733

Number of elements: 140899

3. Boundary conditions for supersonic exhaust diffuser with conical nozzle

Boundary conditions are a set of properties or conditions on surfaces of domains, and are required to fully define the flow simulation. The type of boundary condition that can be set depends upon the bounding surface.

1. Pressure Inlet - Fluid flows into the domain.
2. Pressure Outlet - Fluid flows out of the domain.
3. Opening - Fluid can simultaneously flow both in and out of the domain.
4. Wall - Impenetrable boundary to fluid flow.
5. Axi symmetry Plane - A plane of both geometric and flow symmetry

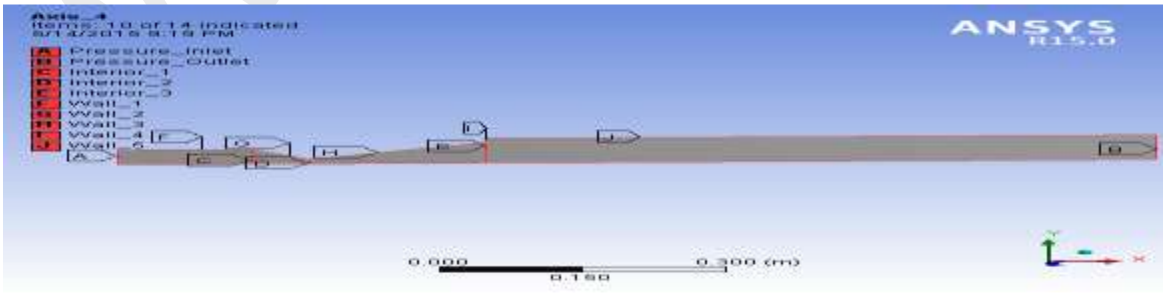

Fig.6 Boundary condition for supersonic exhaust diffuser with conical nozzle

Inlet Pressure	Outlet Pressure
1800000 pa	5000 pa
2000000 pa	5000 pa

Table.2 Inlet and Outlet pressures

4. Flow solver

The flow solver solves the computational problem based on the boundary conditions and the geometry considerations. In the flow solver all the important parameter for solving the internal flows are provided. Here also the turbulence model for the particular geometry is selected. Spalart allmaras turbulence model was used here for flow simulation.

VI. RESULT AND DISCUSSIONS

A. Graphs

1. Mach number Graph

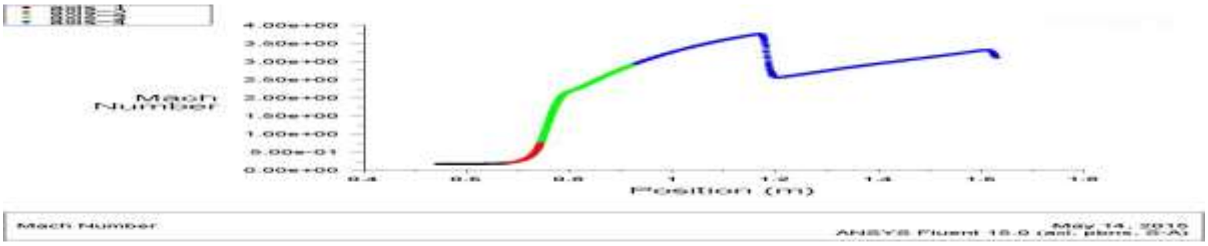

Fig.7 Mach number graph of supersonic exhaust diffuser for length 0.7m with conical nozzle

From the plot of Mach number vs position it shown that the Mach number is increases up to the axis three and then the Mach number reduces from axis four

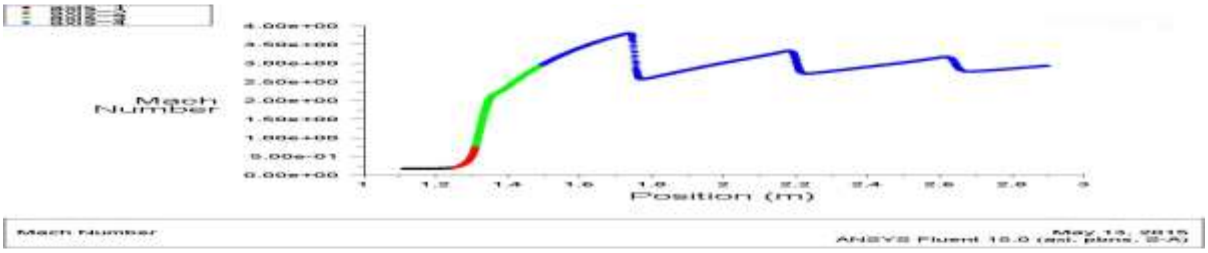

Fig.8 Mach number graph of supersonic exhaust diffuser for length 1.4m with conical nozzle

From the plot of Mach number vs position it shown that the Mach number is increases up to the axis three and then the Mach number reduces from axis four

2. Pressure Graph

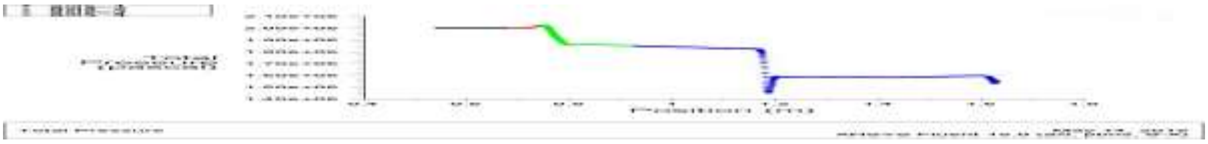

Fig.9 Pressure graph of supersonic exhaust diffuser for length 0.7m with conical nozzle

From the plot of total pressure vs position it shown that the pressure is constant up to axis one and two then the pressure is reduced up to axis four

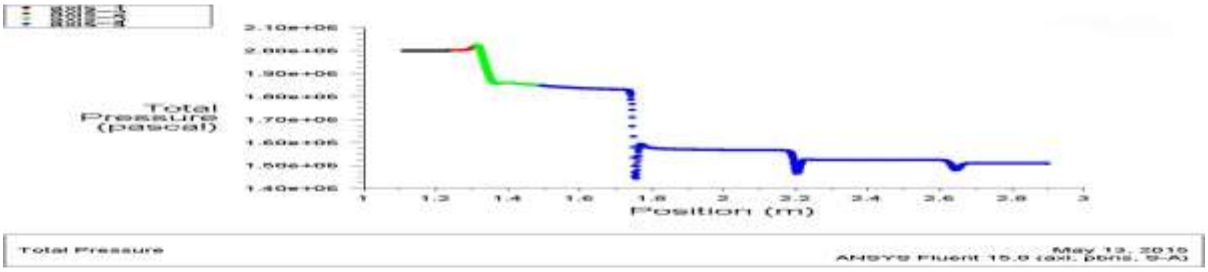

Fig.10 Pressure graph of supersonic exhaust diffuser for length 1.4m with conical nozzle

From the plot of total pressure vs position it shown that the pressure is constant up to axis one and two then the pressure is reduced up to axis four.

B. Flow Simulations

1. Mach number simulation

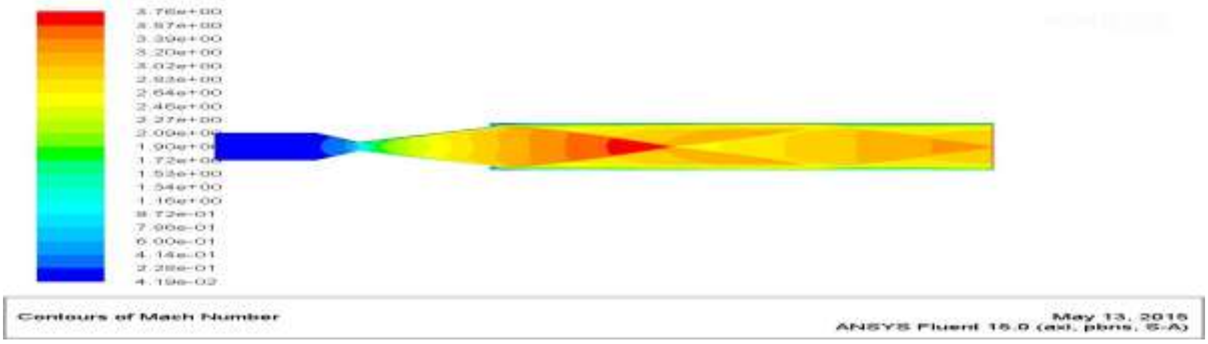

Fig.11 Mach number simulation of supersonic exhaust diffuser for length 0.7m with conical nozzle

The Mach number simulation shows the full expansion condition for the inlet pressure of 1800000 pa and outlet pressure of 5000 pa for the supersonic exhaust diffuser length 0.7m. The Mach number range is of about 3.02 to 3.7.

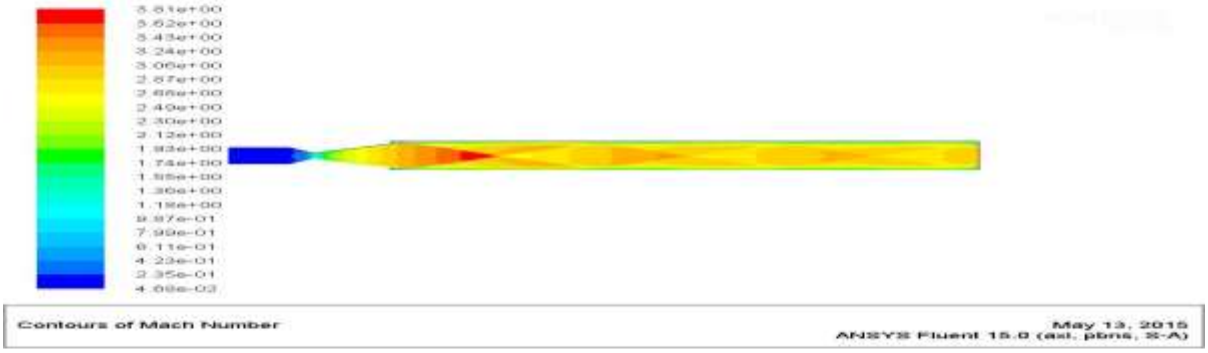

Fig.12 Mach number simulation of supersonic exhaust diffuser for length 1.4 m with conical nozzle

The Mach number simulation shows the full expansion condition for the inlet pressure of 2000000 pa and outlet pressure of 5000 pa for the supersonic exhaust diffuser length 1.4m. The Mach number range is of about 3.06 to 3.81.

3. Pressure simulations

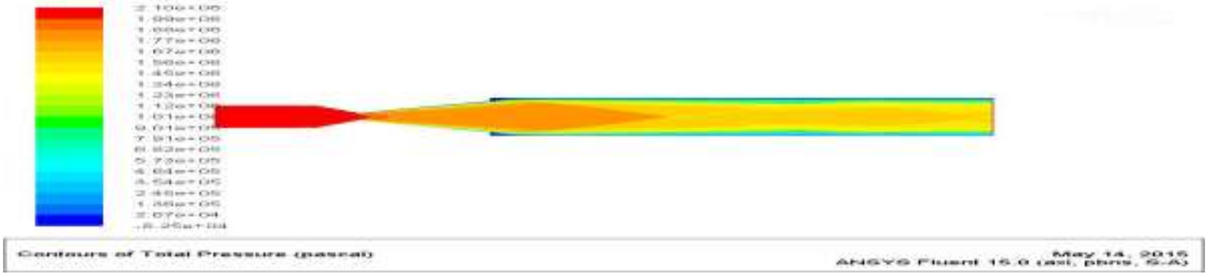

Fig.13 Pressure simulation of supersonic exhaust diffuser for length 0.7 m with conical nozzle

The pressure simulation shows that the maximum pressure was at inlet and the minimum pressure is outlet. So that the velocity of the exit gas was high due to the exit pressure is low.

Fig.14 Pressure simulation of supersonic exhaust diffuser for length 1.4m with conical nozzle

The pressure simulation shows that the maximum pressure was at inlet and the minimum pressure is outlet. So that the velocity of the exit gas was high due to the exit pressure is low.

VII. CONCLUSION

The cfd simulations for supersonic exhaust diffuser of length 0.7m and 1.4m with conical nozzle shows the full expansion with inlet pressure of 18bar, 20bar and the exit pressure of 0.05 bar. This is the actual higher altitude simulation for a two dimensional (2D) conical nozzle with supersonic exhaust diffuser.

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