

## Modelling Nozzle throat as Rocket exhaust

Keshava Rao P.<sup>1</sup>, Komma Rahul<sup>2</sup>, Souda Dinesh<sup>3</sup>

<sup>1</sup>(Mechanical Engineering, CBIT College, India)

<sup>2</sup>(Mechanical Engineering, RGUKT (IIT Basar), India)

<sup>3</sup>(Concurrent Analysis Pvt Ltd, Hyderabad, India)

**ABSTRACT:** The ejector mode of rocket-based combined cycles is a concept that has the ability to gain thrust from atmospheric air and reduce fuel consumption and thus reduce the cost of rocket launches. This thesis develops a three-dimensional rocket nozzle design that includes the potential for incorporating the ejector effect. The nozzle is designed such that the diverging portion of the nozzle geometry must pass through a gate that is placed on the outer perimeter whose shape does not have to remain axisymmetric, thus creating a void for air intake into the centre of an annular rocket exhaust stream. Viscous effects are included via Edenfield's displacement thickness  $\delta$  correlation for turbulent boundary layers. Comparison of computational fluid dynamics to a predefined Mach number distribution is within 1.6% of an inviscid solution and 6.8% for a viscous simulation using the  $k-\epsilon$  turbulence model.

### I. COMBINED CYCLES

Air-augmented rockets also known as Combined Cycles (CC), that present the notion of increasing thrust in addition of mass flow, 70% reducing propellant mass fraction, 10–20% increasing the specific impulse at atmospheric conditions. It leads to reducing launch costs of atmospheric flight. These Cycles are classified as hybrid rocket, operates better than the rocket or ramjet separately.

Combined Cycles is attained through the addition of a diffuser downstream of the exhaust. It includes three parts that is ejector, air intake, thrust chamber. In the thrust chamber propellant energy of fuel converts into kinetic energy accelerating exhaust gases. Through air intake valves air enters into chamber. Ejector effect is achieved by mixing of air and propellant flow. Momentum from the high rocket exhaust velocity is transferred to entrained air. Due to air flow through valves in chamber specific impulse and thrust increases. Ejectors create a vacuum at outlet, reducing the risk of plume overexpansion.

Combined cycle operates at low-altitude environments below 100km identified as von Karman line known to be optimistic upper limit for air augmented systems.

The main aim of this thesis is to show that using CCPS (combined cycle propulsion system) in rockets and other systems in aerospace technology reduces the amount of oxidizer for Trans-atmospheric flight by using oxygen in the atmosphere.

Propulsion systems are classified as CCPS only if all the propulsion subsystems are in use all the times during flight. By this statement turbo ramjet is not classified into CCPS systems.

### II. SUBSYSTEMS OF COMBINED-CYCLE PROPULSION SYSTEMS

The incitement for manufacturing a CCPS is that none of the propulsion systems is effectual throughout the entire range of Mach numbers that an aircraft undergoes. CCPS utilizes two or more subsystems, air-breathing and other systems. The Thrust equation for CCPS is

$$T = mv_2 + ((p_2 - p_3) A_2)$$

Where,

m = mass flow rate,

v<sub>2</sub> = nozzle exit velocity (equal to c)

p<sub>2</sub> = pressure at the nozzle exit

p<sub>3</sub> = pressure of the atmosphere

A<sub>2</sub> = area of the nozzle exit

Effective exhaust velocity (assuming isentropic Flow through the nozzle). This is a reasonable assumption for a converging-diverging nozzle where the maximum fraction of the thermal energy of the gases is converted into kinetic energy in a reversible process

$$v_2 = \sqrt{\frac{2k}{k-1} \frac{R'}{\mathfrak{M}} T_1 \left[1 - \frac{p_2}{p_1}\right]^{\frac{(k-1)}{k}}}$$

k = the ratio of specific heats

R' = universal gas constant

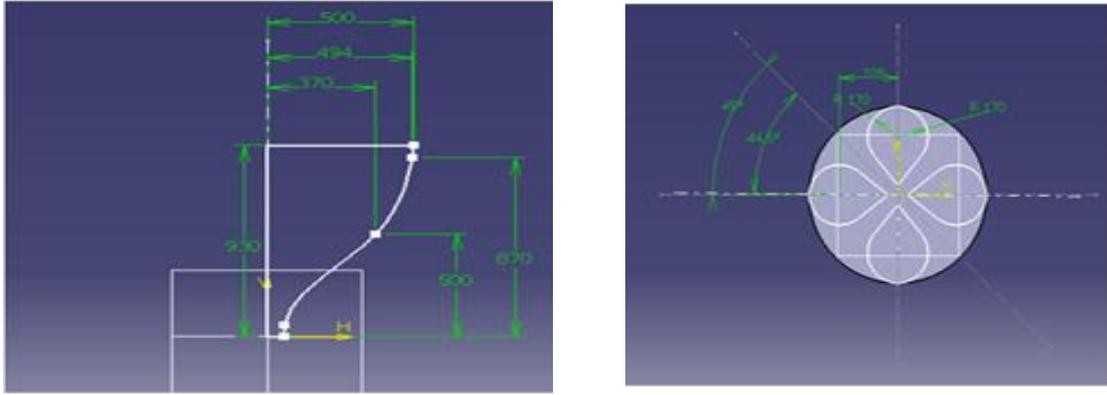
T<sub>1</sub> = stagnation temperature of the chamber or nozzle inlet

$\mathfrak{M}$  = average molecular mass of the fuel

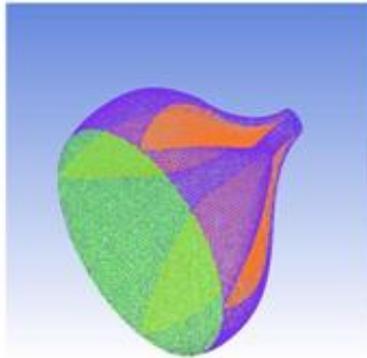
p<sub>1</sub> = chamber pressure

p<sub>2</sub> = pressure at the nozzle exit

**III. MODELLING AND MESHING**

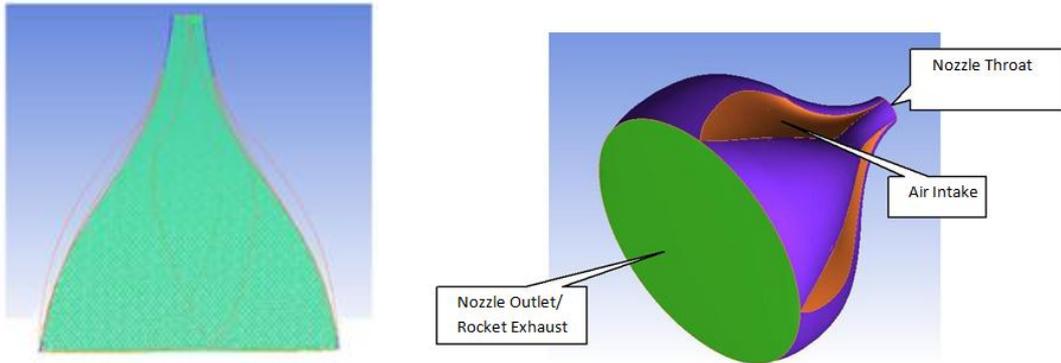


3D Model



**3.1 MESH (ICEM CFD)**

Mesh Type = Tetra/ Mixed  
 Total elements: 6, 55,092



Mesh views

**IV. SIMMULATION**

**4.1 CALCULATIONS**

Speed of Sound depends on temperature and can be calculated using the following formula:

$$\text{Speed of sound } c = 331.5 \cdot \sqrt{\frac{\vartheta + 273.15}{273.15}} = 331.5 \cdot \sqrt{1 + \frac{\vartheta}{273.15}} \text{ in m/s; temperature } \vartheta \text{ in } ^\circ\text{C}$$

By using above formula

Speed of Sound has been calculated as 1060.95 m/sec

For Mach Number 1.05, Velocity at nozzle throat has been calculated as 1114 m/sec

**4.2 MATERIAL USED&BOUNDARY CONDITIONS**

Fluid – Kerosene – Vapour

Chemical Formula – C12H23

Density – 7.1 Kg/m<sup>3</sup>

Thermal Conductivity -0.0178 w/m-k

Viscosity – 7 e-08 Kg/m-s

For Nozzle Throat

Velocity = 1114 m/sec

Supersonic Gauge Pressure = 2475.6 K Pa (2577 Kpa – Operating Pressure (101325 Pa)) Temperature = 3668 K

For Air Intake = Pressure Inlet

For Nozzle Outlet = Pressure Outlet

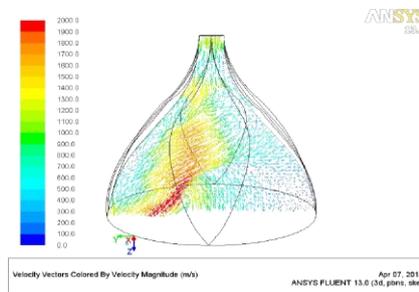
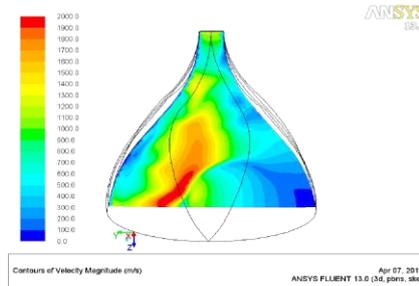
Operating Pressure = 101325 Pa

Wall Temperature = 500 K

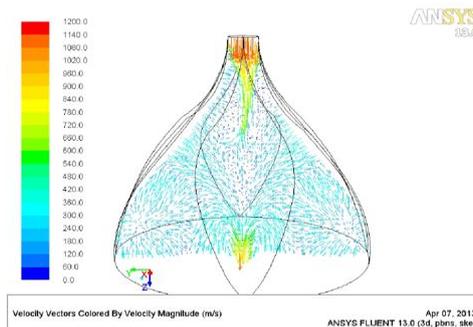
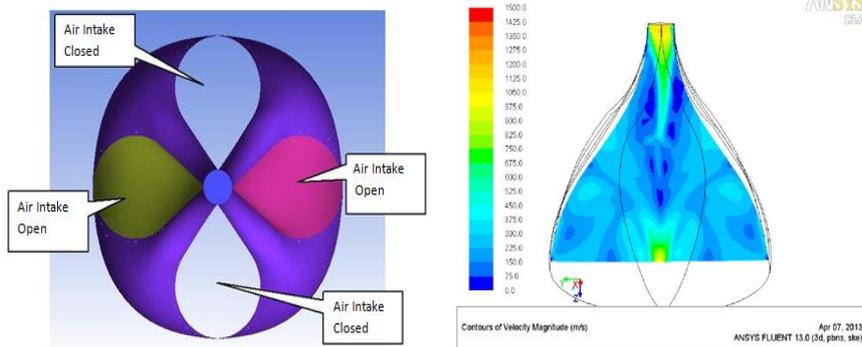
K-ξ Turbulence has been used with 5% as turbulence intensity at boundaries.

### 4.3 COMPARISON OF NOZZLE JET PROPULSION SYSTEM

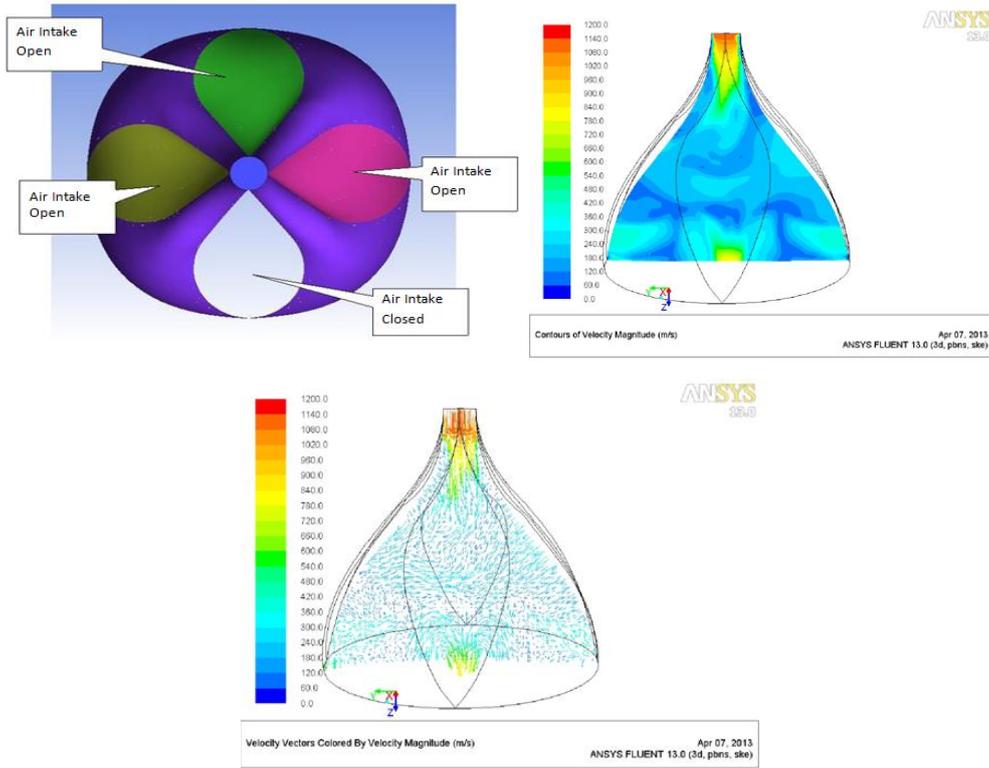
#### 4.3.1 SINGLE AIR INTAKE OPENING



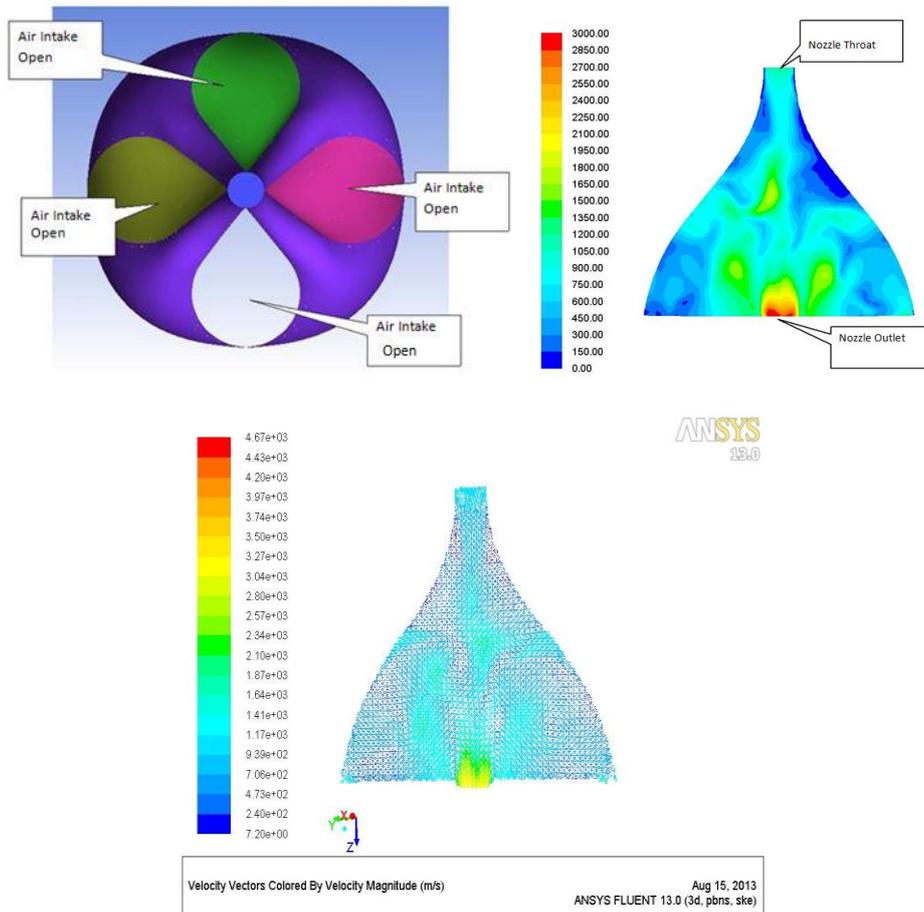
#### 4.3.2 DOUBLE AIR INTAKE OPENING

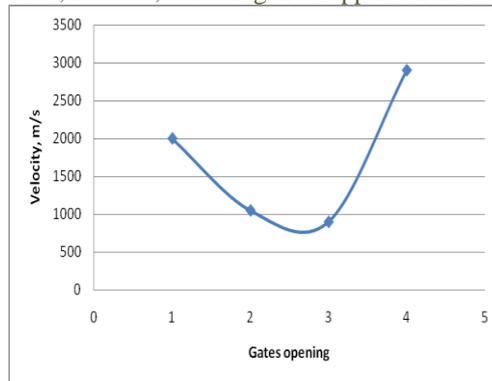


4.3.3 TRIPLE AIR INTAKE OPENINGS

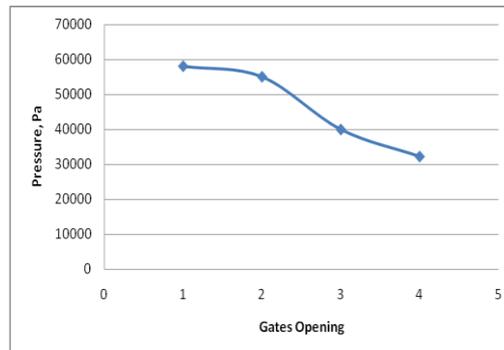


4.3.4 QUADRAPLE AIR INTAKE OPENINGS





Graph between gates opening to the velocity



Graph between gates opening to the Pressure

In the first case even though the velocity of exhaust gases is high (2000 m/s) it is not concentrated exactly at the centre of exhaust opening as shown in velocity contours. Due to this divergence of velocity vector forces act on the walls of nozzle causing manoeuvring and maintenance problems. In the second and Third case the velocity magnitude is low (900-1125 m/s) which is not desirable.

In the fourth case both the velocity of exhaust is high about 2.75 Mach number and the velocity magnitude is concentrated at the correct position at the exhaust.

## V. Conclusion

As a result of void formation air entrainment into the centre of annular rocket exhaust stream occurs.

Isentropic expansion takes place as the wall curvature is convex. Velocity contours diverge into the cross sectional thickness hence velocity first increases along these surfaces.

The direction of the velocity vectors is related to the curvature as the streamlines parallel the nozzle walls

Reduction of the outlet arc angle  $\psi$  should reduce the magnitude of the circumferential velocity components and avoid the likely presence of strong oblique shocks at the nozzle outlet. Increasing the air intake size is beneficial for increased mass flow, the air entrainment capability must consider shock waves or expansion fans induced by the geometry design.

In this thesis comparison among the air inlet with single, double, triple & all open conditions have been performed. Result plots of velocity contours have been published in this report. The highest Mach number of 2.75 (2900 m/sec) occurs in Quadruple air intake case.

Investigation of the specific impulse and thrust performance characteristics are necessary to confirm that the design concept leads to improvement over existing thrust chambers.

## References

- [1] Turner, M. J. L., *Rocket and Spacecraft Propulsion: Second Edition*, Praxis Publishing Ltd., 2005.
- [2] Tajmar, M., *Advanced Space Propulsion Systems*, Springer-Verlag/ Wien, 2003.
- [3] Sutton, G. P., *History of Liquid Propellant Rocket Engines*, American Institute of Aeronautics and Astronautics, 2006.
- [4] Kraemer, R. S., *Rocketdyne: Powering Humans into Space*, American Institute of Aeronautics and Astronautics, 2006.
- [5] Daines, R. and Segal, C., "Combined Rocket and Airbreathing Propulsion Systems for Space-Launch Applications," *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998, pp. 605–12.
- [6] Jones, T. D., "Final countdowns: The shuttle's last years," *Aerospace America*, Vol. 45, No. 1, January 2007, pp. 16–8.
- [7] C'aceres, M., "A sputtering market for nanosats and picosats," *Aerospace America*, Vol. 44, No. 11, November 2006, pp. 16–8.
- [8] Braeunig, R. A., "Rocket & Space Technology," [electronic resource], 2005, URL: <http://www.braeunig.us/space/>, [cited 11 June 2007].
- [9] Shebalin, J.-P. and Tiwari, S. N., "NOZ-OP-2D: A CFD-Based Optimization System for Axially Symmetric Rocket Nozzles," AIAA Paper 2001–1062, 2001, presented at the 31st Joint Propulsion Conference.
- [10] Hagemann, G., Immich, H., Nguyen, T. V., and Dumnov, G. E., "Advanced Rocket Nozzles," *Journal of Propulsion and Power*, Vol. 14, No. 5, September-October 1998, pp. 620–34.
- [11] White, F. M., *Fluid Mechanics*, Boston: McGraw-Hill, 5th ed., 2003.
- [12] Hopkins, D. F. and Hill, D. E., "Transonic Flow in Unconventional Nozzles," *AIAA Journal*, Vol. 6, No. 5, 1968, pp. 838–42.