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Design and Estimation of HTC in CD Nozzle using Bartz's Equation

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Abstract*: Convergent-Divergent nozzle, CD nozzle is a tube with an asymmetric hourglass shape with converged diameter at the center, assembling the nozzle precisely and perfectly balanced. Convergent-Divergent nozzle rushes pressurized hot gas flowing at supersonic speed at thrust direction by converting heat energy into kinetic energy. With this advantage the Convergent-Divergent nozzle is used in many types of Steam Turbines, Rocket Engine nozzles and Supersonic Jet Engines. The present paper describes the design of CD nozzle in solid works and study of heat transfer coefficient in CD nozzle using D.R. Bartz equation.

Keywords: CD nozzle, D.R. Bratz equation, heat transfer coefficient (HTC), Mach number.

I. INTRODUCTION

The Convergent-Divergent nozzle was first developed (independently) by Ernst Körting in 1878, was a German Engineer and Inventor and Gustaf de Laval in 1888, who was a Swedish inventor for use on a Steam Turbine.

The flow of fluids flowing at subsonic and supersonic speeds depends on various properties of fluids at the nozzle. As the pipe carrying gas converges there will be increase in flow of speed of subsonic glow gases. This occurs due to the constant mass flow rate. In a de Laval nozzle, the entropy of gas flowing through the gases fluid in subsonic flows through the gases is constant. Sound waves flows through the gases fluid in subsonic flow. The velocity if the gases becomes sonic i.e. march number = 1 at the minimum cross-sectional area and this condition is known as Choked flow. With increase in the cross-section area of the nozzle the gas. The gases start to increase its velocity to supersonic speeds, at this state the sound wave doesn't propagate backwards through the gas. i.e. Mach No > 1.

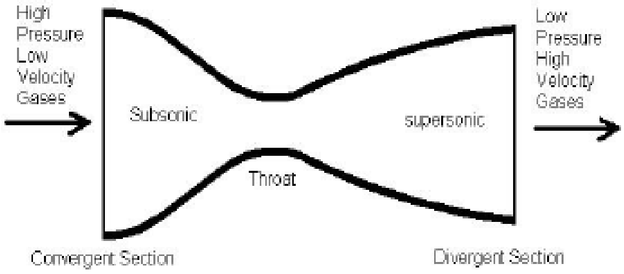

Fig 1: Convergent-Divergent nozzle.

The pressure and mass flow rate through the convergent section are enough to reach the sonic velocity and at the throat section the nozzle starts to choke. If the flow doesn't reach supersonic velocity, then its acts as an venturi meter. For entering into a nozzle, the flow requires to have an entry pressure which must be significantly higher than the ambient pressures at all the situations (similarly, the ambient pressure of the surroundings must be lower then the stagnation pressure of the flow).

Also, the exhaust pressure of the nozzle must not be too low. As the pressure will not flow upstream into the supersonic flow, the outlet pressure i.e. the exhaust pressure can be below the ambient pressure. But it should not be too far below the ambient pressure, as it may cause the flow to discontinue despite being at supersonic velocities, or the flow may start to diverge within the divergent portion of the nozzle, forming an unstable flow that may "debacle" inside the CD nozzle, generating a lateral thrust and presumably damage it.

The pressure of the supersonic gas at the outlet of the supersonic flow which leaves the nozzle should not be greater than approximately 2-3 times the ambient pressure.

Many factors such as geometrical dimensions, gas flow rate percentage, compressibility, non-Iso-Thermicity, length of the preconnected section, roughness, chemical reactions, etc. Will affect the intensity if the heat transfer in nozzles. Using D.R Bratz's equation the Heat Transfer in nozzles were determined. Gas flow rate and nozzle dimensions were the primary parameters considered in this equation. The effects of the other factors were also taken into consideration somewhat arbitrarily. Further useful data can be achieved by merging experimental data with the theoretical techniques which consider the longitudinal development of the Thermal Boundary layer.

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The approximate theoretical solutions are obtained form D.R. Bratz's equation for all the problems of heat transfer in nozzles. In this equation, the "Arithmetic Mean" of characteristic Temperature is obtained by a frictional law for an in compressible gas extended to include compressibility.

Based on certain effective length, D.R. Bratz suggested a calculation method which takes a consideration of the record of the previously developed history of the boundary layer. With the help of relative heat transfer laws of energy equations, a solution has been developed.

A simplified technique of determining the heat transfer in nozzles is been reviewed by this paper.

II. D.R. BARTZ'S EQUATION:

Comparing with the predictions of D.R. Bratz's Nusselt number correlation equation and his method of explaining the boundary layer momentum and energy equation concurrently for the heat transfer coefficient, the experimental or analytical heat transfer coefficient are measured in the convergent divergent nozzle.

In these dates, many attempts have been made to predict the Heat Transfer rates analytically in the combustion chamber of the nozzle along with the walls of the rocket nozzle of solid and liquid propellant rocket engines. Researches have been developing predications methods in the field of Liquid Propellant Rocket Engines, with most of them are successful in determining the heat loads for various types of engines. D.R. Bratz has forwarded two most broadly used techniques for determining the Heat Transfer Rates. The first technique of predicting the heat transfer rate was made using Nusselt Number correlation equation which was developed way before the arrival of high-speed computers and is still being used for rapid estimation of heat transfer rates. The second technique of prediction requires to solve the boundary layer momentum equation and energy equation, for determining the solution of the heat transfer coefficient, a high-speed computer is required to solve the problem. The above two methods are being implemented on to a solid propellant rocket engine nozzle. The experimental results or data on the heat transfer rates for this type of rocket motor is not extensive, it is difficult to conclude the applicability of D.R. Bratz's methods over solid propellant engines. Most of the solid propellant rocket engines are not cooled externally, and most of the design of the solid propellant motors or engines are based on the material of the nozzle wall, which will be absorbing the heat from the exhaust gases of the propellant. The critical temperature gradients are kept through the nozzle wall, while after the of ignition, therefore this condition must be taken into consideration during the design phase. The prediction of the heat loads should be accurately being designed to maximize the efficiency of the nozzle.

To provide further test data, the heating rates in the convergent-divergent nozzle were measured by two points first one at the convergent region at the throat, second being at the divergent region at the throat, using small solid propellant rocket. The heating rates were measured by the by the thermocouples mounted perpendicular to the heated surface of the nozzle.

In this paper, a CD nozzle is designed in sold works and using Computational Fluid Dynamics(CFD) software the heat transfer coefficient is calculated and are compared with the predictions of D.R. Bratz Nusselt number correlation equation and with the method of solving the boundary layer momentum and energy equations for heat transfer coefficient.

For solving these equations, the basic assumptions made by D.R. Bratz are as follows:

1. The flow is always Axisymmetric and steady. Pressure Gradients are the only force acting on the flow. Surface Resistance at the wall and the boundary layer is small when compared to the distance from the axis of symmetry.
2. The flow through the nozzle is adiabatic and reversible with the change in total enthalpy of gas is due to heat flux to the wall.
3. The gas is perfect and has a constant Prandtl number, its viscosity is similar to the gas temperature raised to a power.
4. The surface friction coefficient and the Stanton number are same as they would be on flat plate at the same free flow condition, wall temperature and momentum thickness.
5. Heat transfer either does not affect the surface friction coefficient as C_f is the same as for the adiabatic flow or has an effect as the C_f is the same for adiabatic incompressible flow with the density and viscocity evaluated at the arithmetic mean of the wall and free flow static temperatures.
6. The temperature distributions and the boundary layer velocity are $1/7^{th}$ the power profiles.

With the following assumptions in place the heat transfer coefficient is calculated theoretically.

III. DESIGN AND ANALYSIS OF CD NOZZLE.

A model of CD nozzle is developed using solid works software, using the given specifications:

- Inlet diameter: 150 mm.
- Outlet Diameter: 300 mm.
- Convergent angle: 45 degrees.
- Divergent angle: 15 degrees.
- Radius of curvature: 100 mm.
- Diameter at throat: 100 mm.

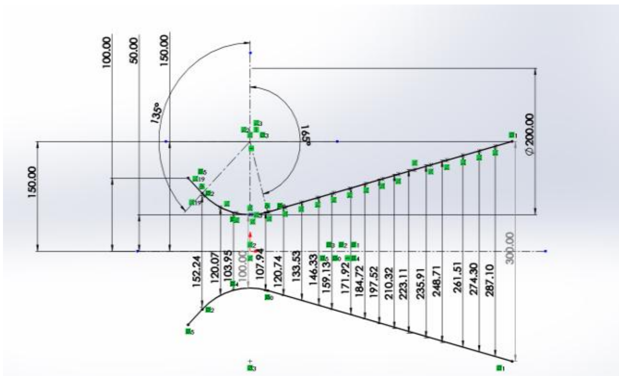

Fig 2: Design of the rocket nozzle.

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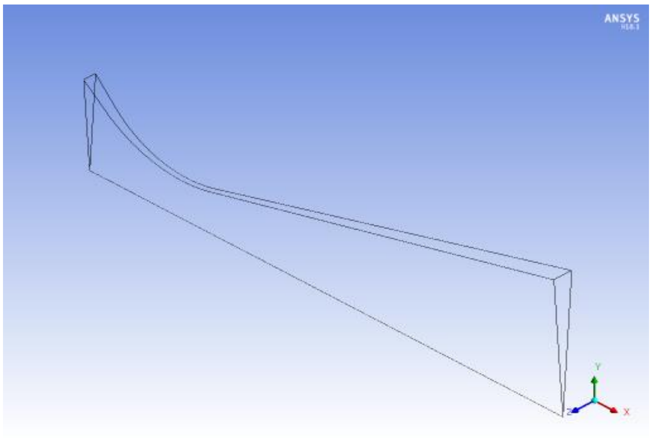


Fig 3: Wire frame model of a rocket nozzle.

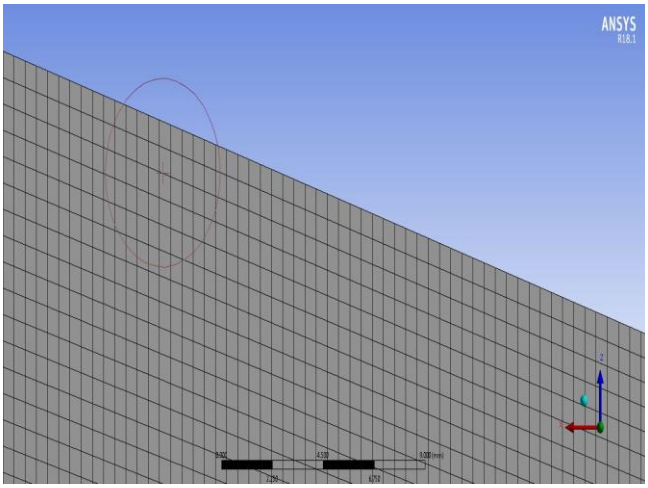


Fig 4: Zoomed version of nozzle showing the meshing done.

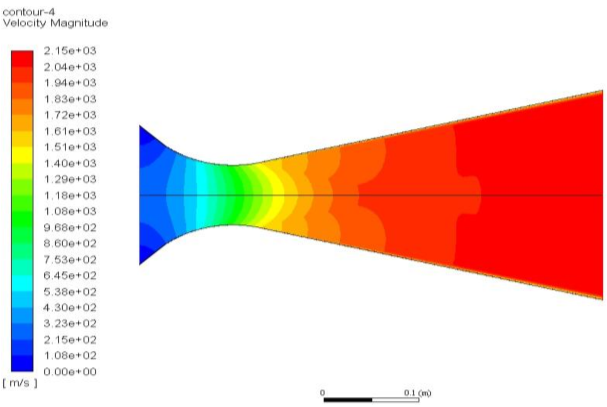
IV. RESULTS AND DISCUSSIONS

With the help of Ansys Fluent software, simulation of flow analysis with input as:

- Input temperature: 3000K.
- Wall temperature: 1000K
- Input pressure: 5 mPa or 5000000 Pa.

Comparation between theoretical and analytical results of various parameters are discussed below:

Velocity: variation of velocity of air through the nozzle.



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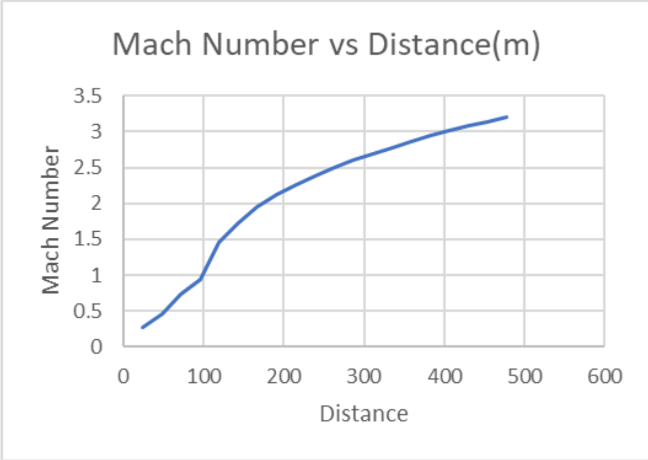
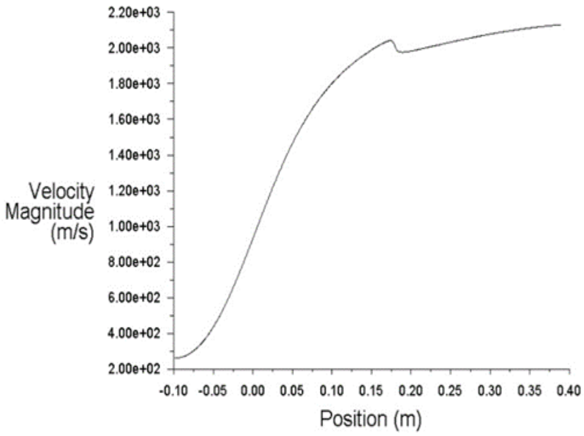


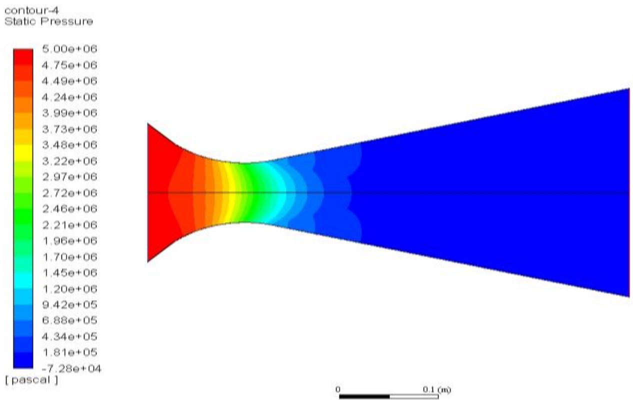
The above graph represents the variation of velocity (Mach Number) w.r.t the distance inside the nozzle. The Mach number increases exponentially inside the nozzle. As the pressure inside the nozzle decreases alone the horizontal axis of the nozzle, in turn increaseing the velocity.

Analytical (CFD):



The above graph represents the variation of velocity w.r.t the position of nozzle. The velocity of the air increases rapidly along the aaxis of flow and position of flow. There is small glitch in the graph, it occurs when there is a sudden change in the cross-sectional area of the nozzle.

Pressure: variation of pressure of air through the nozzle.



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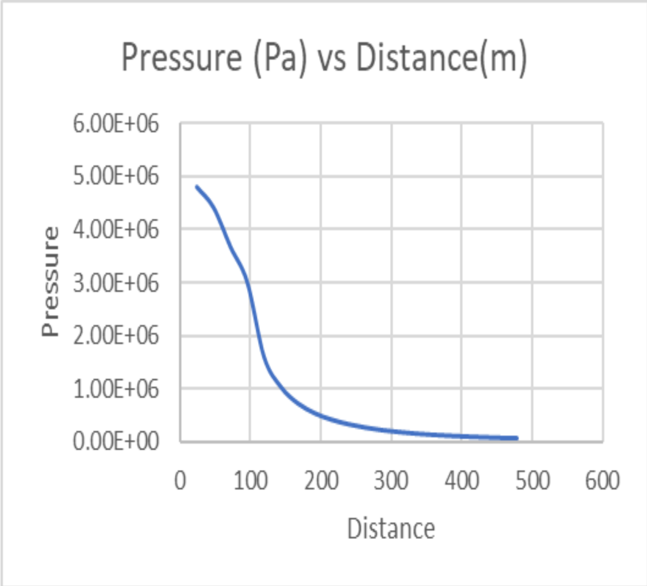
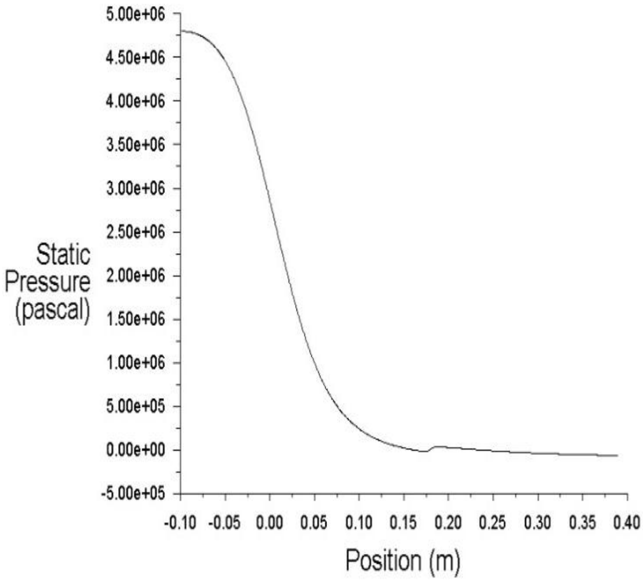


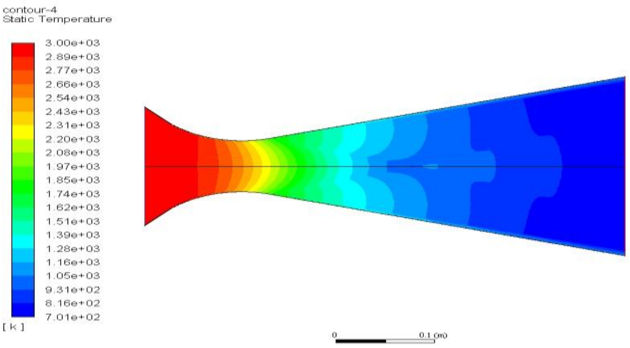
The above graph represents the variation of the pressure w.r.t the distance along the nozzle. The pressure of air decreases rapidly as the area of cross-section of the nozzle decreases.

Analytical (CFD):

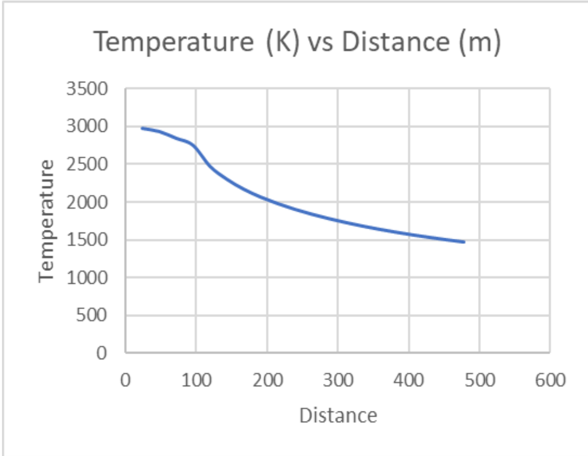


The above graph represents the variation of pressure w.r.t the position of the nozzle. The pressure of air decreases rapidly as the cross-sectional area of the nozzle decreases.

Themeperature: Variation of temperature of air through the nozzle.

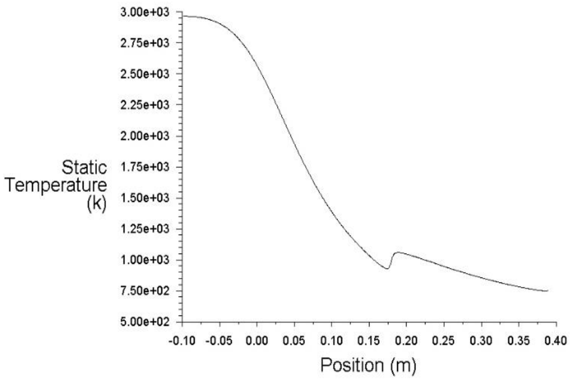


Theoretical:



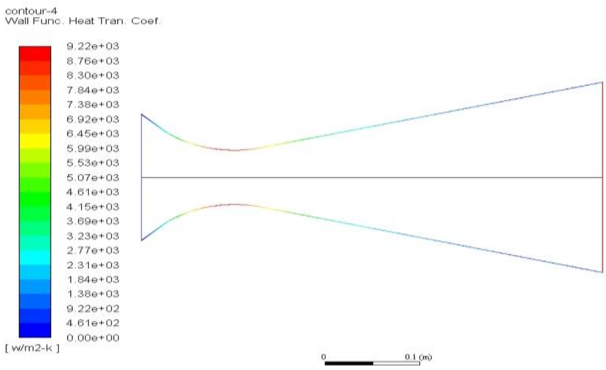
The above graph represents the variation of temperature w.r.t the distance of the nozzle along the axis of flow. The variation of temperature is appoximately linear in state as the cross-sectional area of the nozzle decreases in a steady level.

Analytical(CFD):



The above graph represents the variation of tem[erature w.r.t the position of the nozzle. The temperature of the air decreases exponentially as the cross-sectional area decreases slowly and the small glitch occurs when there is a sudden change in the cross-sectional area of the nozzle.

Heat transfer coefficient: The variation of heat transfer coefficient of wall throughout the nozzle.



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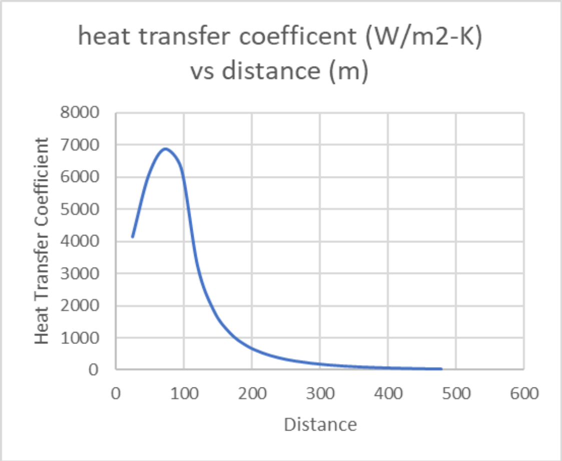
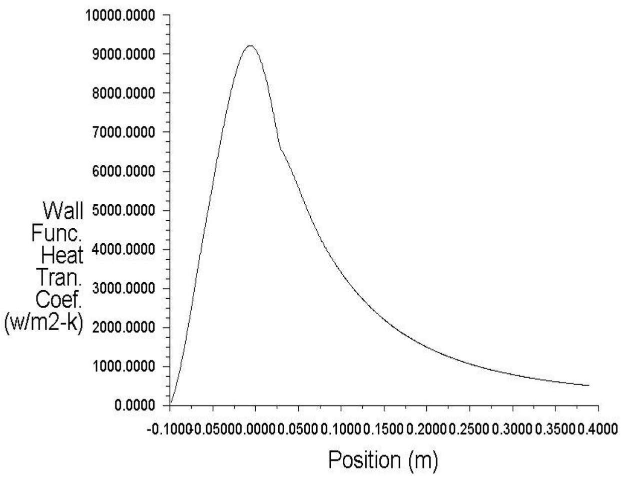


The above graph represents the variation of the heat transfer coefficient w.r.t the distance of the nozzle along the axis os flow. The maximum heat transfer coefficient is found at the throat section which is equal to 6870.33W/m^2-K.

Analytical(CFD):



The above graph represents the variation of heat transfer coefficient w.r.t the position of the nozzle. The maximum heat transfer coefficient is found at the throat section which is approximately equal to 9200 W/m^2-K.

V. CONCLUSION

In the "**Estimation of heat transfer rates inside CD nozzle**" the heat transfer rate is always maximum at the throat region and this can be proved theoretical by D.R. Bratz equation i.e. "**D.R. Bratz – A simple equation for rapid estimation of rocket nozzle convective heat transfer coefficients.**" To find convective heat transfer rates in the rocket nozzles, this is used. To prove it practically, we performed an analysis on the conditions set by D.R. Bratz equation in **Computational Fluid Dynamics** software. Firstly, a rocket nozzle was constructed in solidworks software with the required dimensions and conditions of a rocket nozzle. Then with the help of Ansys Fluent software i.e. Computational Fluid Dynamics Software, we have performed the simulations of the rocket nozzle in controlled and known conditions. After obtaining the results from the Computational Fluid Dynamics software, we have compared them with the theoretical calculations and found that the analytical calculations (Computational Fluid Dynamics) were 22% more than the theoretical calculations. Hence, we can conclude that D.R. Bratz's equation was much relevant to the present-day calculations.

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