Optimization of a Formula SAE Intake Restrictor for Maximum Pressure Recovery using Computational Fluid Dynamics

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Abstract - *The Formula SAE (FSAE) competition mandates the use of a single circular restrictor within the intake manifold positioned between the throttle body and the engine to effectively limit the maximum power output of the internal combustion engine. Because this restrictor introduces a physical bottleneck, it often results in significant pneumatic losses that can hinder volumetric efficiency. This research focuses on the design, simulation, and optimization of a Venturi-style intake component engineered to comply with FSAE regulations while maximizing pressure recovery. Using Ansys Fluent for high-fidelity Computational Fluid Dynamics (CFD) analysis, the study focuses on minimizing the total pressure loss caused by skin friction and flow separation. The methodology involved an iterative parametric study of the convergent and divergent nozzle sections. The simulation identifies the configurations that best preserve the kinetic energy of the flow and convert it back into static pressure before it reaches the plenum. The simulations evaluated a wide matrix of angular combinations. Results indicate that a converging angle of 12° combined with a diverging angle of 6° yields the optimal pressure recovery profile. The 12° entry angle provides a smooth transition to the throat, minimizing the vena contracta effect, while the shallow 6° exit angle effectively manages the adverse pressure gradient to prevent boundary layer separation. These findings provide a data-driven framework for FSAE teams to maximize engine air-intake pressure, thereby reclaiming potential horsepower lost to regulatory constraints.*

Key Words: Formula SAE, Restrictor Design, Venturi Effect, Pressure Recovery, Computational Fluid Dynamics, Volumetric Efficiency, Boundary Layer Separation, Parametric Optimization.

1. INTRODUCTION

SAE SUPRA is a premier engineering competition organized by SAE INDIA. The event operates under a unique industry-based premise: a fictional firm contracts a student design team to develop a small, Formula-style race car intended for the non-professional, weekend autocross market.

To succeed, student teams must manage multiple engineering departments to design, build, and test a prototype that adheres to a rigorous set of technical regulations. The competition evaluates these open cockpit, open-wheel vehicles through two distinct categories:
Static Events: Focusing on design logic, cost efficiency, and business presentation.
Dynamic Events: Testing the car's performance, reliability, and speed on the track.

Teams accrue points based on their performance in each category, with the final rankings determined by the cumulative score across all tests. This challenge pushes students beyond the classroom, requiring them to excel in both high-level engineering and project management.

To ensure competitor safety and limit the maximum power capability of the engines, the **SAE SUPRA India Rulebook 1)** mandates the use of a single circular restrictor. This restrictor must be placed in the intake system between the throttle body and the engine, and all intake airflow must pass through it. For a single-cylinder engine, this restrictor is limited to a 20mm diameter.

At low rpm this restrictor has negligible effect on the engine's performance but as an engine's RPM increases, it demands a higher volume of air. This air must pass through the 20mm throat of the restrictor. According to the principle of continuity, as the cross-sectional area decreases at the throat, the velocity of the air must increase.

When the air velocity at the narrowest part of the restrictor (the throat) reaches the local speed of sound (Mach 1), the flow becomes "choked", this starts to happen at around 15000 rpm. At this point, the air can no longer accelerate further, regardless of how much the engine's suction increases or how much the downstream pressure drops. Consequently, the mass flow rate through the system reaches a fixed maximum value and can no longer increase to meet higher engine demands, effectively capping the engine's performance.

So for this constant mass flow rate of 0.074282 kg/s we need to design a venturi which allows for maximum pressure recovery so that air sent to the engine is at maximum pressure allowing for best volumetric efficiency. Maximizing pressure recovery also minimizes pumping losses.

The objective of this study is to perform a parametric optimization of the converging and diverging angles of a 20mm restrictor. By iterating through various geometric combinations in a virtual CFD environment, this research identifies the configuration specifically 12° converging and 6° diverging that yields the maximum pressure recovery for the engine intake.

2. Literature Review

2.1 Historical Foundations and Fundamental Principles of Gas Dynamics

The fundamental relationship between cross-sectional area and flow velocity in compressible fluids was first mathematically established by **Hugoniot** in the late 19th century. This theory was practically realized through the development of the convergent-divergent nozzle by **Gustaf de Laval**, which demonstrated that sonic velocity (M=1) occurs exclusively at the minimum area, or throat. This research applies these classical principles of gas dynamics to the specific geometric constraints of the SAE SUPRA 20mm restrictor.

The primary challenge in SAE SUPRA powertrain design is the intake restriction mandated by the competition rules. According to the **SAE India Rulebook 1)** all air must pass through a single circular 20mm orifice. In the literature regarding gas dynamics, this creates a 'choked flow' condition as the engine speed increases.

2.2 The Choked Flow Phenomenon and Theoretical Mass Flow Limits

As established by **Frank M White** and **Anderson 2)**, the theoretical maximum mass flow rate ($\dot{m}$) through a sonic throat is independent of the downstream suction (pressure drop) once Mach 1 is reached. This is defined by the isentropic choked flow equation:

$$\dot{m} = \frac{AP}{\sqrt{T}}\sqrt{\frac{\gamma}{R}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

For a 20mm throat (A= 0.000314 m^2) at standard ambient conditions, this results in a fixed limit of approximately 0.074282 kg/s.

2.3 Impact of Restriction on Volumetric Efficiency (η_v) and Density

Previous studies by **Sowter et al. 3)** on restricted racing engines emphasize that once the "choked" state is reached, the engine's air consumption is physically capped. This confirms that at high RPM, the intake system no longer functions as a variable-flow device, but as a constant-mass-flow regulator. Consequently, researchers agree that the engineering challenge shifts from "pulling more air" to preserving the quality specifically the stagnation pressure of the air that does pass through.

The primary limit of a restricted engine is the reduction in the mass of air trapped in the cylinder during the intake stroke. As established by **Heywood 4)**, Volumetric Efficiency (η_v) is defined as the ratio of the actual mass of air inducted into the cylinder to the mass that would occupy the displaced volume at ambient conditions.

Literature consistently shows that (η_v) is a direct function of the intake manifold pressure (P_i). When air passes through a 20mm restrictor, it loses static pressure. If this pressure is not "recovered" in the diverging section, the air entering the cylinder is at a lower density (ρ). According to the Ideal Gas Law (ρ = P/RT), a higher recovered pressure at the intake valve directly increases the density of the charge. **Taylor 5)** notes that for every 1% increase in intake pressure recovered through an optimized Venturi, a nearly linear increase in η_v is observed, allowing the engine to burn more fuel and produce higher peak torque despite the 20mm bottleneck.

2.4 Pumping Work and Manifold Pressure Dynamics

As defined by **Heywood 4)**, Pumping Work (W_p) is the net work done by the piston on the in-cylinder gases during the intake and exhaust strokes. In a naturally aspirated engine limited by a 20mm restrictor, the intake stroke often occurs at a pressure significantly below atmospheric. This creates a negative pressure differential across the piston. The Pumping Mean Effective Pressure (PMEP) represents the specific work required to overcome this restriction. Literature by **Ganesan 6)** establishes that as the intake manifold pressure (P_{im}) drops due to flow restrictions, the PMEP increases, directly subtracting from the Gross Indicated Mean Effective Pressure (IMEP) to yield a lower **Net** Indicated Mean Effective Pressure (IMEP).

The culmination of increased η_v and decreased pumping losses is a measurable gain in Brake Power. Research by **Sowter et al. 3)** into Formula Student powertrains found that engines limited by a 20mm restrictor are highly sensitive to "Inlet Stagnation Pressure." Their research highlights that maximizing pressure recovery does not just move the "choke point" to a higher RPM, but it raises the entire torque curve across the power band.

2.5 Comparative Analysis: Orifice Plate vs. Venturi Geometry

As established by **White 7)** a standard thin-plate orifice typically exhibits a C_d in the range of 0.60 to 0.65. In contrast, a well-designed Venturi meter characterized by streamlined converging and diverging sections can achieve C_d values between 0.95 and 0.99.

The literature explains this drastic difference through the phenomenon of the Vena Contracta. In an orifice, the fluid streamlines cannot turn 90° sharply at the edge; they continue to contract even after passing through the physical hole, resulting in an "effective" flow area that is significantly smaller than the 20mm diameter. In a Venturi, the converging section guides the streamlines smoothly to the throat, effectively eliminating the Vena Contracta and ensuring that the physical area is fully utilized for mass flow.

Beyond the flow capacity, the "permanent pressure loss" is the most critical factor for engine performance. **Fox and McDonald 8)** demonstrate that an orifice plate creates high levels of turbulence and large-scale eddies downstream of the restriction. Because an orifice lacks a diverging section, the high kinetic energy at the throat is dissipated as heat and noise through "abrupt expansion," leading to a permanent loss of stagnation pressure.

Conversely, a Venturi utilizes a gradual diverging section to perform Pressure Recovery. **Miller 9)** notes that by decelerating the flow slowly, the kinetic energy is converted back into static pressure. Research indicates that while an orifice may lose over 80% of the pressure drop created at the throat, a Venturi can recover up to 90% of that pressure, ensuring the engine receives air at a density much closer to ambient conditions.

In the context of SAE competition rules, the 20mm restrictor is a mandatory bottleneck. **Sowter et al. 3)** performed comparative tests on FSAE engines and concluded that using an orifice-style restrictor causes "premature choking" and a massive deficit in peak power. Their findings suggest that the low C_d of an orifice makes the 20mm hole behave like a 16mm or 17mm hole in terms of mass flow capacity.

Modern literature in the field of automotive aerodynamics **Katz, 10)** emphasizes that the Venturi is the only viable solution for high-performance intake systems. By maximizing the C_d, the Venturi allows the engine to reach its theoretical mass flow limit (0.0742kg/s) with the least possible Pumping Loss. This is supported by recent CFD studies which show that the streamlined geometry of a Venturi maintains laminar-to-turbulent transition more effectively than the "sharp-edge" flow of an orifice, which triggers immediate and chaotic flow separation.

2.6 Geometric Optimization: Symmetry and Continuity

The fundamental objective of a Venturi in a restricted engine is to act as a temporary "velocity transformer." According to Bernoulli's Principle, the total energy of the flow is the sum of its static pressure and its dynamic pressure (velocity head). As established by **White 7)**, for a "Zero-Sum" energy exchange, the outlet conditions must mirror the inlet conditions. If the inlet diameter (D_1)equals the outlet diameter (D_2), the cross-sectional areas are identical. By the Continuity Equation, this forces the outlet velocity (V_2) to equal the inlet velocity (V_1). Literature suggests that this symmetry ensures that no energy is "trapped" as excess kinetic energy at the exit; instead, the maximum possible amount of kinetic energy from the throat is converted back into static pressure for the engine to use. This avoids the 'kinetic energy trap' of smaller outlets and the turbulent expansion losses associated with larger outlets, thereby maximizing the stagnation pressure delivered to the engine plenum

In internal flow systems, energy dissipation that occurs due to changes in geometry is quantified by the Minor Loss Coefficient (K**)**. The head loss (h_L) associated with these changes. Research by **Munson et al. 11)** emphasizes that in high-velocity racing intakes, these "minor" losses are often major contributors to total pressure drop. When $D_1 \neq D_2$, the system introduces one of two parasitic K-factors.

- When $D_{out}>D_{in}$ the air exits the Venturi into a larger diameter than it entered, it undergoes an expansion. Literature by **Fox and McDonald 8)** shows that sudden expansions create large recirculation zones (eddies) at the corners of the step. These eddies do not contribute to flow; they simply consume the air's kinetic energy and dissipate it as heat, leading to a permanent drop in stagnation pressure.

- When $D_{out}<D_{in}$ the outlet is smaller than the inlet, the flow is forced into a permanent state of higher velocity. The K-factor for contraction (K_{con}) is typically around 0.5 for a sharp step. However, the more significant loss is the increased Skin Friction. According to the Darcy-Weisbach equation, friction losses are proportional to V^2. By forcing a smaller D_{out}, the velocity V remains high throughout the rest of the intake runner, exponentially increasing the "parasitic drag" of the air before it reaches the cylinder.

The efficiency of the pressure recovery is limited by the Diffusion Ratio**. Miller 9)** establishes that as the area ratio increases, the adverse pressure gradient becomes more severe. If D_{out} is significantly larger than D_{in}, the air must work harder to stay attached to the walls over a larger area change. To reach a larger D_{out} without triggering Boundary Layer Separation, the Venturi would require an excessively long diverging section. By maintaining $D_1 = D_2$, the design achieves a "natural" diffusion ratio that matches the engine's throttle body and runner size.

In SAE SUPRA applications, the Venturi is a link in a chain. **Heywood 4)** notes that "Flow Quality" the uniformity of the velocity profile is critical for cylinder filling. A mismatch in diameters ($D_1 \neq D_2$) creates "velocity skew" or turbulence at the junction. Literature in automotive fluid dynamics **Katz [**Error! Reference source not found.] suggests that a seamless, equal-diameter transition ensures that the air entering the plenum is stable and laminar. This reduces the work required by the plenum to distribute air evenly to all cylinders, thereby improving the engine's Volumetric Efficiency (η_v).

2.7 Converging Section Design: Balancing Separation and Friction

The primary function of the converging section is to accelerate the air from the inlet diameter to the 20mm throat with minimal energy loss. The literature identifies the Discharge Coefficient (C_d) as the key metric for this section. According to **White [**Error! Reference source not found.**]**, the optimal total included angle for a nozzle-style convergence is typically between 12° and 14° .This range represents a critical balance between two competing fluid-mechanical losses:

- Separation Losses**:** If the angle is too steep (>20°) the air cannot follow the wall contour at the throat entry, leading to a Vena Contracta. This effectively "shrinks" the 20mm hole, reducing the mass flow capacity.
- Frictional Losses**:** If the angle is too shallow (<10°), the converging section becomes unnecessarily long. As the surface area increases, the cumulative Skin Friction (viscous drag) begins to significantly drop the total pressure before the air even reaches the throat.

2.8 Diverging Section Design: The Physics of Pressure Recovery

The diverging section (the diffuser) is the most sensitive part of the intake system. Its goal is Pressure Recoveryconverting high-velocity kinetic energy back into static pressure. The success of this section is measured by the Pressure Recovery Coefficient (C_p).

The literature establishes a "Golden Rule" for diffusers: the angle must be shallow enough to prevent the Adverse Pressure Gradient from triggering Boundary Layer Separation. **Fox and McDonald 8)** demonstrate through performance charts that the peak C_p for a conical diffuser occurs at a total included angle of 6°to 7°.

- The "Diffuser Stall" Limit: As the air slows down, the pressure increases. This "climb" in pressure pushes against the incoming air. If the angle exceeds 7°, the momentum of the air near the wall is insufficient to overcome this pressure "hill," causing the flow to peel away and create Recirculation Zones.
- Length Constraints: While an angle of 3° or 4° would technically be even safer against separation, **Miller 9)** notes that the resulting length would cause excessive frictional losses that outweigh the benefits of the attachment.

Consequently, the consensus in the literature **Katz** Error! Reference source not found. is that 6° to 7° is the global optimum for high-velocity internal flows, offering the highest possible static pressure at the engine plenum.

2.9 The Quasi-Steady Assumption in High-RPM Intake Systems

While internal combustion engines are inherently transient due to the periodic opening and closing of intake valves, the literature frequently employs the Quasi-Steady Assumption for manifold component design. As established by **Heywood 4)**, at high engine speeds (RPM), the time scales of the intake pulses become small relative to the fluid velocity through the restrictor.

Blair 12) notes that for the purpose of geometric optimization specifically the determination of discharge coefficients (C_d) and pressure recovery steady-state flow testing and simulation provide a highly accurate "mean" representation of the system's performance. The literature suggests that if a geometry performs optimally under steady-state conditions, it typically maintains that superiority under pulsating conditions because the fundamental fluid-dynamic losses (friction and separation) remain tied to the local Reynolds numbers.

The 20mm restrictor adds a unique layer of stability to the flow. According to **Anderson** Error! Reference source not found.**,** once the flow reaches a "choked" or sonic state (M=1) at the throat, the mass flow rate becomes "locked" and independent of downstream pressure fluctuations.

- Acoustic Isolation**:** Literature by **Sowter et al 3)** demonstrates that the sonic throat acts as an acoustic barrier. Downstream pressure waves (pulses from the valves) cannot travel upstream through the M=1 section.
- Steady-State Validity**:** Because the throat "filters" the pulsations from reaching the inlet, the flow through the converging and throat sections behaves as a purely steady-state phenomenon. This justifies using steady-state CFD to calculate the maximum mass flow capacity with high precision.

3. Methodology

3.1 Inlet and Outlet Geometry Selection

The geometry of the Venturi was designed to ensure a seamless interface with the vehicle's induction system while maximizing pressure recovery.

- Dimensional Alignment: The inlet and outlet diameters were established at 46.0 mm to maintain consistency across the assembly.
- Inlet Rationale: A 46.0 mm inlet diameter provides a 1:1 match with the internal bore of the throttle body,

eliminating "step-losses" and premature flow separation at the entry plane.

- Outlet Rationale: As established in the literature review, the outlet diameter was set to 46.0 mm to facilitate optimal pressure recovery by returning the flow to the induction system's primary diameter.
- Zero-Parallel Design: To minimize the total wetted surface area and associated skin friction, the design utilizes a sharp entry lip (zero radius) and transitions directly into the converging and diverging sections without parallel entry or exit buffers.

3.1 Theoretical Mass Flow Derivation

To establish the target boundary conditions for the simulation, the maximum theoretical mass flow rate through the 20 mm circular restriction was calculated based on the physics of Choked Flow (M = 1). Under these conditions, the air velocity at the throat reaches the local speed of sound, limiting the maximum throughput regardless of downstream pressure drops.

The mass flow rate ($\dot{m}$) was determined using the following isentropic relationship for a compressible fluid:

$$\dot{m} = \frac{AP}{\sqrt{T}}\sqrt{\frac{\gamma}{R}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Constants and Parameters Used:

- Mach Number (M)=1 (Choked state)
- Throat Area (A)= 0.000314 m^2 (Calculated for a 20 mm diameter)
- Inlet Pressure (P_i)=101,325 Pa (Standard ambient)
- Total Temperature (T)=300 K
- Gas Constant (R)=0.287 kJ/kg. K (for Air)
- Ratio of Specific Heats (γ)=1.4
- Resulting Mass Flow Rate: 0.074282 kg/s

3.2 Computational Meshing Strategy

A high-fidelity discretization strategy was employed to ensure results were independent of grid density, particularly at the 20 mm throat.

- Mesh Density: The final production methodology refined the grid to exceed 200,000 elements.
- Quality Metrics: The mesh was optimized to ensure a high Orthogonal Quality (averaging > 0.95) and a Max Aspect Ratio below 16.

3.3 Solver Physics and Material Properties

The simulation was conducted using a 3D, double-precision, steady-state approach to analyze peak flow conditions.

- Turbulence Modelling: The SST k-omega model was selected as it combines the stability of k-epsilon in the free-stream with the high accuracy of k-omega near the walls.
- Material Properties: Air was modelled as an Ideal Gas. This accounts for the compressibility effects and density drops that occur as the air reaches high subsonic velocities.
- Energy Equation: Heat transfer was enabled to account for temperature changes during high-speed expansion.
- Numerical Discretization: A Green-Gauss Cell Based evaluation was used for gradients. To ensure high-order accuracy, Second-Order Upwind discretization was applied to the momentum, density, energy, and turbulence equations to minimize numerical diffusion.

3.4 Boundary Conditions

The boundary conditions were configured to represent the peak mass flow demand of the engine pulling from the ambient atmosphere.

- Inlet Boundary: A Pressure Inlet was utilized with a Gauge Total Pressure of 0 Pa and a Total Temperature of 300 K to simulate ambient atmospheric entry.
- Outlet Boundary: Mass Flow Outlet was set to a constant rate of 0.074282 kg/s.
- Choked Flow Equation: This mass flow rate was calculated using the choked flow equation, representing the physical limit of air that can pass through the 20 mm throat at a Mach number of 1.
- Operating Pressure: The simulation utilized a standard operating pressure of 101,325 Pa.

3.5 Convergence and Solution Validation

The simulation was run for 1,000 iterations to ensure the stability of the result.

- Residual Monitoring: Convergence was assessed by tracking the residuals for continuity, momentum (x, y, z), energy, and turbulence (k-omega).
- Convergence Criteria: All residual monitors were strictly set to a target of 10^{-6} to ensure a high-fidelity mathematical solution.
- Solution Stability: The solution was validated once the net mass flow balance between the inlet and

outlet planes reached a stable state with an error below 0.1%.

Result Analysis: The centreline velocity magnitude was tracked to confirm that the peak velocity correctly corresponds to the minimum area at the 20 mm throat.

4. Results and Discussion

4.1 Pressure Drop Comparison Matrix

The primary performance indicator for the Venturi restrictor is the total pressure drop (ΔP). A minimized pressure drop ensures higher manifold pressure and superior volumetric efficiency for the 600cc engine. The following matrix summarizes the calculated total pressure drop for each configuration, grouped by diverging angle to illustrate the impact of geometry on performance:

Table -1: Pressure drop for each design iteration

Configuration	Total Pressure Drop (ΔP)
12C / 6D	5,005.42
13C / 6D	6,098.01
14C / 6D	7,117.54
12C / 7D	7,278.37
13C / 7D	6,425.55
14C / 7D	6,641.57

4.2 Pressure Contours

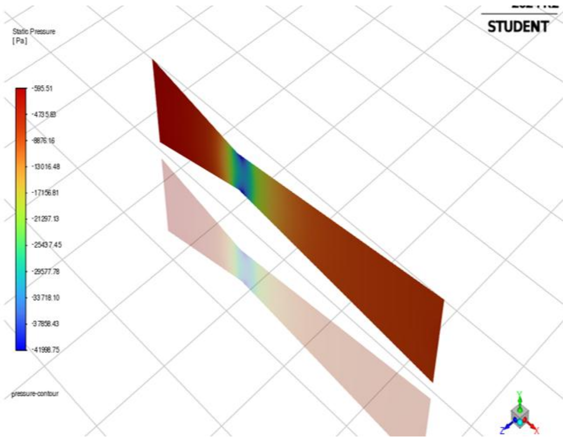

Fig -1: Pressure contour for converging angle 12° and diverging 6° of venturi

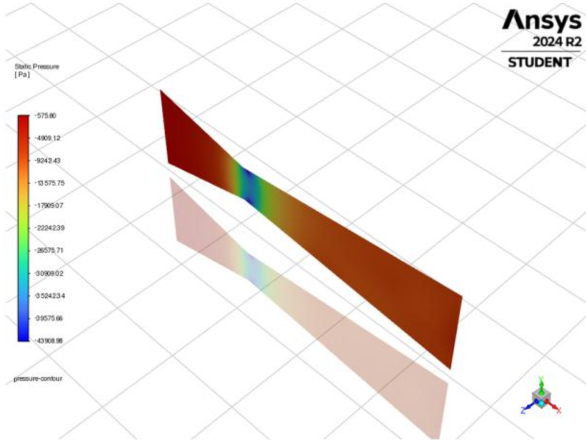

Fig -2: Pressure contour for converging angle 13° and diverging 6° of venture

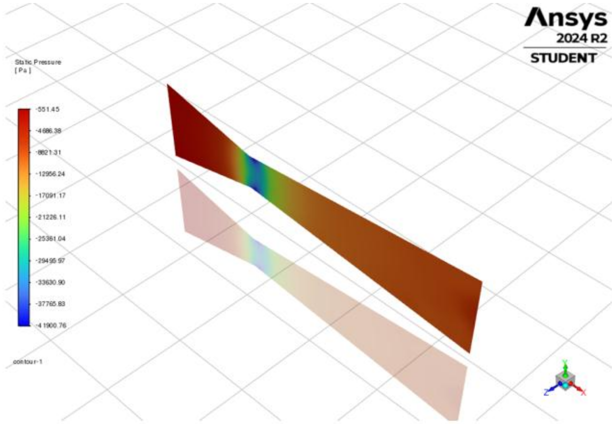

Fig -3: Pressure contour for converging angle 14° and diverging 6° of venture

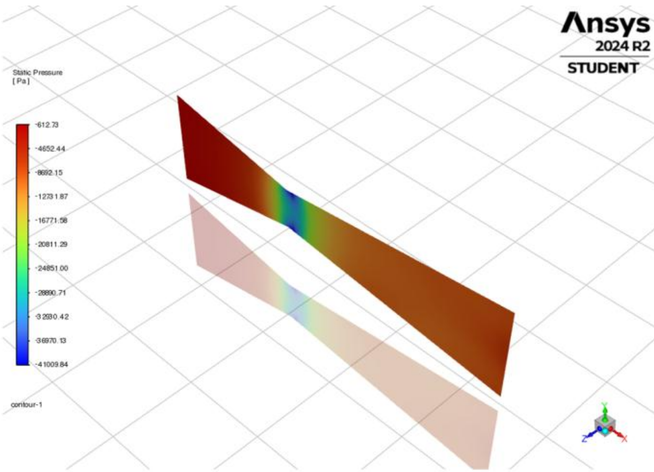

Fig -4: Pressure contour for converging angle 12° and diverging 7° of venturi

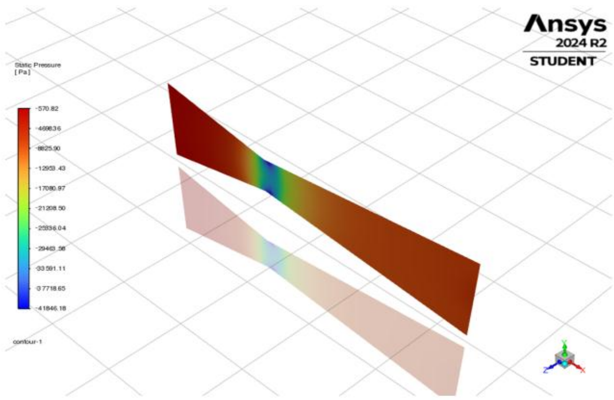

Fig -5 Pressure contour for converging angle 13° and diverging 7° of venturi

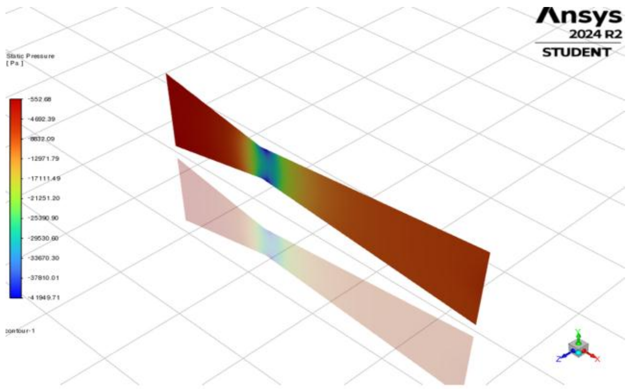

Fig -6 Pressure contour for converging angle 14° and diverging 7° of venture

5. CONCLUSIONS

This research successfully optimized a 20 mm circular Venturi restrictor for a 600cc engine through a parametric study of six geometric configurations. The primary objective was to minimize the total pressure drop across the 46 mm induction system while maintaining the required mass flow rate under choked flow conditions. The 12C / 6D configuration was identified as the most aerodynamically efficient geometry, achieving the lowest total pressure drop of 5,005.42 Pa.

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