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DESIGN AND ANALYSIS OF VERTICAL AXIS WIND TURBINE BLADES FOR MINI POWER GENERATION

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Abstract:

This study presents the design and performance analysis of a Savonius-type Vertical Axis Wind Turbine (VAWT) optimized for decentralized mini power generation in urban settings, such as powering traffic signals. Designed to deliver approximately 1 kW of electricity at low wind speeds (2 m/s), the turbine capitalizes on the Savonius configuration’s advantages—omnidirectional operation, self-starting ability, and efficiency in turbulent wind conditions. A structured Analytic Hierarchy Process (AHP) was employed to evaluate five blade materials across nine mechanical and thermal criteria, identifying AISI 422 stainless steel as the optimal choice. Blade modeling in CATIA V5, followed by aerodynamic and structural simulations in ANSYS Fluent and Mechanical, confirmed the design's aerodynamic efficacy and structural integrity. The results validate the turbine’s feasibility for urban energy harvesting, with future enhancements suggested through solar integration, IoT-based monitoring, and advanced materials for scalability and efficiency.

Keywords — **Savonius vertical VAWT. Low Wind Speed Generation, Analytic Hierarchy Process (AHP), Aerodynamic and Structural Simulation**

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I. INTRODUCTION

1.1 Overview of Wind Energy

Wind energy is one of the most promising and rapidly expanding forms of renewable energy. It harnesses the kinetic energy of wind and converts it into electrical power using wind turbines. As a clean, sustainable alternative to fossil fuels, wind energy significantly contributes to global decarbonization goals and supports the transition to net-zero carbon economies. The working principle of wind energy involves the rotation of turbine blades by wind force, which drives a rotor connected to an electrical generator, thereby producing electricity.

1.2 Comparison: Horizontal Axis vs. Vertical Axis Wind Turbines

Wind turbines are primarily classified into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) based on the orientation of their rotation axis. The table-1 compares the two types across several performance and design characteristics:

Feature	**Horizontal Axis (HAWT)**	**Vertical Axis (VAWT)**
Axis of Rotation	Horizontal (parallel to wind direction)	Vertical (perpendicular to wind direction)
Wind Direction Requirement	Requires yaw control to face wind	Omnidirectional – no yaw system needed

Feature	**Horizontal Axis (HAWT)**	**Vertical Axis (VAWT)**
Installation Height	Tall towers required	Operates at lower heights
Maintenance	Difficult (elevated systems)	Easier (ground-level access)
Efficiency	High in open terrain	Lower for large-scale use, better in low-speed zones
Startup Wind Speed	~10 m/s	As low as 2 m/s
Noise & Aesthetics	Noisier and more visually intrusive	Quieter and better suited for urban environments
Suitability for Urban Use	Less suitable	Highly suitable due to compact form factor

While HAWTs dominate large-scale wind farms, VAWTs are increasingly seen as favorable for urban and decentralized applications due to their unique structural and operational advantages.

1.3 Advantages of Vertical Axis Wind Turbines (VAWTs)

VAWTs present multiple benefits, particularly when designed for small-scale or urban use:

- Omni directional Operation: No need for wind tracking mechanisms, allowing operation from any wind direction.
- Low Startup Speed: Capable of initiating rotation at wind speeds as low as 2 m/s.
- Compact & Scalable: Suitable for space-constrained environments like rooftops or residential plots.
- Low Center of Gravity: Enhances mechanical stability and simplifies maintenance.
- Noise Reduction: Operate with less acoustic impact, ideal for urban and residential settings.
- Bird Safety: Lower tip speeds reduce risk to avian life.

1.4 Applications of Mini Wind Turbines

Mini wind turbines are an emerging solution for localized and off-grid energy needs, particularly where solar-only systems are inadequate. They are used in:

- Residential and small commercial power systems
- Electrification of rural and remote areas
- Mobile and nomadic power setups (e.g., boats, RVs)
- Communication towers and IoT infrastructure
- Hybrid renewable systems (with solar panels)
- Small-scale irrigation and agricultural systems

1.5 Why VAWTs are Ideal for Mini Power Generation

Vertical Axis Wind Turbines offer several characteristics that align with the goals of mini power generation systems:

- Space Efficiency: Their vertical form allows deployment in constrained spaces.
- Urban Wind Adaptability: Perform effectively in turbulent and inconsistent wind conditions.
- Enhanced Safety & Aesthetics: Lower risk profiles and less visual intrusion support their integration into urban landscapes.
- Cost-Effectiveness: Lower installation height and simpler maintenance procedures contribute to reduced operational costs.

1.6 Current Trends and Research Gaps

The evolution of wind turbine technology has witnessed significant innovation aimed at enhancing urban wind energy integration. Notable current trends include:

- Urban Rooftop Integration: Deployment of VAWTs on residential and commercial rooftops.
- Hybrid Systems: Co-locating VAWTs with photovoltaic systems for improved reliability.
- Innovative Blade Designs: Implementation of biomimetic forms (e.g., inspired by fish

fins or birds) for performance improvement.

- Noise and Vibration Reduction: Development of silent turbine blades and dampening systems.
- **Smart Materials & 3D Printing**: Leveraging additive manufacturing and adaptive materials for cost reduction and customizability.

Despite these advancements, gaps remain in areas such as **material optimization for cost-performance trade-offs**, **long-term durability analysis under urban load profiles**, and **integration with smart grid and IoT systems**, justifying the continued need for focused research in this domain

II. LITERATURE SURVEY

The global pursuit of renewable energy has propelled vertical axis wind turbines (VAWTs) into focus, particularly the Savonius rotor for its suitability in low-speed and turbulent urban wind conditions. Unlike horizontal axis turbines, VAWTs do not require wind alignment mechanisms and are more adaptable to confined environments, making them ideal for mini power generation. This section reviews recent advancements in VAWT blade design, simulation techniques, and material selection strategies.

2.1 Savonius Rotor Design and Performance in Urban Settings

Marmutova (2016) conducted a CFD study on the aerodynamic behavior of Savonius rotors installed in urban environments. Her work concluded that Savonius turbines perform more reliably in turbulent, multidirectional wind fields when compared to conventional rotors, although their power coefficient remains lower than Darrieus designs.
Ang and Honra (2025) proposed a novel three-blade Savonius rotor design incorporating pointed deflectors. Their study coupled CFD with FEA to validate both aerodynamic efficiency and structural integrity, emphasizing the importance of blade geometry and load resilience in low-wind conditions.

2.2 Material Selection and Structural Analysis Using FEA

Mat Yazik et al. (2023) highlighted the effect of material roughness and type on Savonius blade performance. Their integrated CFD-FEA approach assessed different materials under various load cases and established the relevance of composite materials in urban VAWT systems. Farajyar et al. (2023) conducted an optimization study using CFD on a Savonius turbine for a hybrid solar-wind urban system. The study also explored installation layouts for maximizing wind interception, reinforcing the importance of environmental placement in design phases.

2.3 Integrated CFD and FEA in VAWT Design

Ageze and Tigabu (2022) examined CFD methodologies and material selection impact on the H-Darrieus and Savonius hybrids, stressing the need for mesh refinement and turbulence model validation in small-scale turbine simulations.

Ennadafy et al. (2025) modeled a PVC-based helical VAWT with CFD and FEA tools to evaluate load stress and aerodynamic efficiency. Their study reinforced the viability of lightweight thermoplastics in VAWT blade fabrication for urban use.

2.4 CFD-Driven Blade Optimization and Material Innovation

Marinić-Kragić et al. (2022) performed a global optimization on Savonius rotors using a validated 3D CFD model. Their findings emphasized the role of circular arc blade geometry in improving power coefficients in low-speed conditions. Ghoneam et al. (2021) employed the Taguchi method integrated with CFD to optimize composite blades for dynamic loading. This hybrid technique allowed precise material tuning for fatigue resistance and performance stability.

2.5 Review on Emerging Trends in Urban VAWT Systems

Kumar et al. (2018) provided a comprehensive review of VAWT systems for urban deployment, identifying Savonius rotors as optimal due to low startup speed, safety, and cost-effectiveness. The review also documented simulation tools used across published studies. Mathaiyan et al. (2022) summarized recent VAWT innovations and emphasized multi-criteria material selection frameworks, like AHP and PROMETHEE, for sustainable blade design.

Summary

Across the reviewed studies, several key themes emerge:

- CFD and FEA are now standard in design validation, allowing deeper insights into blade aerodynamics and stress behavior.
- Material selection plays a central role in both mechanical performance and lifecycle cost, especially under low-speed wind loading.
- Urban VAWT deployment demands compact, lightweight, and safe systems that can endure turbulent flow.
- Savonius rotors continue to be the most practical for decentralized applications due to simplicity and adaptability

III. DESIGN ASPECTS OF SAVONIUS BLADES

3.1 Justification for Choosing the Savonius Rotor

While several vertical axis wind turbine (VAWT) designs exist—including the Darrieus rotor, H-Darrieus rotor, and helical blade configurations—the Savonius rotor was chosen for this project due to its distinctive advantages in urban and low-wind applications.

Simplicity in Design

The Savonius rotor features a mechanically straightforward design, typically composed of two or more semi-cylindrical scoops. This simplicity allows for cost-effective fabrication and assembly using widely available materials. Its uncomplicated structure also contributes to lower maintenance requirements and increased durability over time.

Efficient Operation in Low Wind Speeds

One of the most significant advantages of the Savonius design is its ability to initiate rotation at low wind speeds—often as low as 2 m/s. This characteristic makes it particularly suitable for environments with inconsistent or minimal wind flow, such as urban centers and semi-urban terrains.

Omnidirectional Performance

Unlike horizontal axis wind turbines (HAWTs), which require a yaw mechanism to align with the wind direction, Savonius turbines operate effectively from any wind direction. This omnidirectional functionality simplifies installation and enhances reliability in locations with variable or unpredictable wind patterns.

Compactness and Structural Robustness

The vertical axis orientation and lower profile of the Savonius rotor make it more compact and suitable for constrained urban spaces. Additionally, the structure is less exposed to dynamic wind loads, reducing mechanical stress and increasing resistance to gust-related failures.

Superior Performance in Turbulent Environments

Savonius turbines are particularly effective in turbulent wind conditions often found in built-up environments. The drag-based design provides reliable power generation even when wind patterns are erratic and disturbed by nearby buildings or structures.

Low Noise Emissions

Due to lower rotational speeds and less complex blade geometries, Savonius turbines produce minimal operational noise. This attribute makes them favorable for use in residential areas, campuses, and other noise-sensitive locations.

Self-Starting Capability

Savonius rotors exhibit excellent self-starting behavior, beginning rotation without the need for external power inputs or auxiliary mechanisms. This is a key operational benefit, especially for decentralized, off-grid systems.

Durability and Low Maintenance

With fewer moving components compared to other turbine types, the Savonius rotor is more durable and less prone to wear and mechanical failure. This translates to extended operational lifespans and reduced lifecycle costs.

3.2 Blade Geometry and Aerofoil Profiles

Although the Savonius turbine primarily utilizes drag-based motion rather than lift, the understanding of blade profiles remains crucial for aerodynamic refinement:

- **Aerofoil Shape**: More critical in Darrieus and H-type turbines, where lift dominates.
    - Common profiles include **NACA 0012**, **NACA 0015**, and **NACA 0021** for performance optimization.
- **Blade Thickness and Camber**: Influences both the structural strength and aerodynamic behavior.
- **Aspect Ratio**: Higher aspect ratios (longer, thinner blades) generally yield better aerodynamic efficiency, albeit with structural trade-offs.

3.3 Materials Used for Blade Construction

Material selection plays a critical role in turbine performance, balancing mechanical strength, cost, and manufacturability. Common blade materials include:

- **Fiberglass**: Lightweight and affordable; widely used in small wind turbines.
- **Carbon Fiber Composites**: Excellent strength-to-weight ratio; higher cost.
- **Aluminum Alloys**: Durable and corrosion-resistant but heavier.
- **Wood or Bamboo**: Cost-effective and sustainable; suitable for very small-scale applications.
- **Stainless Steel (AISI 422)**: Selected for this project due to its strength, corrosion resistance, and manufacturability.

3.4 Fundamental Performance Metrics

Torque (T)

Torque refers to the rotational force produced by aerodynamic interactions with the turbine blades. It is directly influenced by blade radius, wind speed, and aerodynamic force acting on the blade surface.

Power Co-efficient (Cp)

The power coefficient is a dimensionless metric used to evaluate turbine efficiency, defined as the ratio of actual power output to the theoretical maximum power available in the wind (Betz Limit = 59.3%).

$$Cp = \frac{P_{actual}}{\frac{1}{2}\rho A V^3}$$

Where:
P_{actual} = Actual power output
ρ = Air density
A = Swept area
V = Wind speed

3.5 Design Parameters and Scaling Considerations

For this study, the turbine was designed to generate approximately **1 kW of power** at a wind speed of **15 m/s**, although it is optimized for low-wind startup. The **rotor height and diameter** were derived using power equations incorporating wind speed, air density, and estimated Cp values.

Key design parameters include:

- **Cut-in Speed**: Minimum wind speed to initiate turbine rotation.
- **Rated Speed**: Wind speed at which the turbine reaches maximum rated power.
- **Rotor Diameter**: Determines the swept area, directly affecting power output.
- **Turbine Height**: Influences exposure to higher wind speeds and reduces turbulence effects.

3.6 Aerodynamic Performance Factors

Static Pressure Distribution

The **static pressure distribution** on blade surfaces is a critical aerodynamic indicator. It reflects how effectively the blades are interacting with the wind to generate torque. In CFD simulations (e.g., ANSYS Fluent), pressure contour plots reveal regions of:

- **High pressure on the windward side** and **low pressure on the leeward side**, indicating effective torque generation.
- **Asymmetrical flow fields**, due to blade orientation relative to wind direction.
- **Stagnation zones and pressure drop-offs**, which help identify drag hotspots or potential flow separation.

These pressure variations govern the generation of rotational force and hence directly impact turbine performance.

IV. MATERIAL SELECTION FOR TURBINE BLADE USING ANALYTIC HIERARCHY PROCESS (AHP)

4.1 Overview of AHP Methodology

The **Analytic Hierarchy Process (AHP)** is a structured multi-criteria decision-making (MCDM) technique developed by Thomas Saaty. It is widely used to solve complex engineering problems where several conflicting criteria must be evaluated simultaneously. In the context of wind turbine blade design, AHP enables systematic comparison of potential materials by quantifying subjective preferences and translating them into objective rankings.

The AHP process involves the following key steps:

1. **Problem Definition and Criteria Identification**
   The primary objective is defined — in this case, the **selection of an optimal material for turbine blade construction**. Nine evaluation criteria are established to guide decision-making.
2. **Decision Hierarchy Formation**
   The problem is decomposed into a three-level hierarchy:
   - **Level 1**: Goal (Material selection)
   - **Level 2**: Decision criteria
   - **Level 3**: Alternative materials
3. **Pairwise Comparisons**
   Each criterion is compared with the others using Saaty's 1–9 scale to determine relative importance. Similarly, each material is compared under each criterion.
4. **Matrix Normalization**
   The comparison matrices are normalized by dividing each matrix element by the sum of its respective column.
5. **Priority Vector Calculation**
   The average of normalized rows provides the local priority vector, indicating the relative weight of each criterion or alternative.
6. **Consistency Check**
   A consistency ratio (CR) is computed to ensure the judgments are logically coherent. A CR less than 0.1 is generally considered acceptable.
7. **Synthesis and Final Ranking**
   The weights of criteria are combined with the rankings of alternatives to derive a **global score** for each material. The material with the highest score is selected.

4.2 Implementation for Wind Turbine Blade Material Selection

4.2.1 Alternative Materials Considered

Five candidate materials were evaluated as feasible options for blade manufacturing in small-scale Savonius-type vertical axis wind turbines:

1. **AISI 422 Stainless Steel**
2. **Aluminum**
3. **Fiberglass**
4. **Carbon Fiber Composites**
5. **High-Density Polyethylene (HDPE)**

4.2.2 Selection Criteria

Nine decision-making criteria were chosen based on mechanical, thermal, and economic performance relevant to urban turbine deployment:

No.	Criterion	Description
1	**Cost**	Overall material cost, including fabrication feasibility
2	**Toughness**	Resistance to impact and crack propagation
3	**Corrosion Resistance**	Suitability for outdoor and humid environments
4	**Density**	Affects weight and structural design load
5	**Young's Modulus**	Measure of stiffness under mechanical stress
6	**Hardness**	Resistance to deformation or wear
7	**Thermal Conductivity**	Relevant for material response to fluctuating temperatures
8	**Thermal Capacity**	Heat absorption and dissipation characteristics
9	**Thermal Expansion**	Dimensional stability under temperature variations

4.3 Final Decision

Each material was evaluated against the above criteria using the AHP framework. The final synthesis of weights and performance scores yielded **AISI 422 Stainless Steel** as the most suitable material. This selection was driven by its balanced mechanical properties, durability, and economic viability, particularly in applications subjected to environmental exposure and fluctuating stress loads.

The AHP analysis thus provided a transparent and defensible method for material selection, ensuring alignment with both performance and cost objectives of the wind turbine project

Final Ranking

Rank	Material	Priority
1	Steel	0.30580
2	Aluminum	0.24170
3	Carbon Fiber	0.20535
4	Fiberglass	0.16800
5	HDPE	0.09051

V. MODELLING AND ANALYSIS

5.1 CAD Modelling of Turbine Blades

The geometric modeling of the vertical axis wind turbine (VAWT) blade was performed using **CATIA V5**, a powerful parametric CAD tool widely used in aerospace and mechanical design. The blade geometry was based on the **NACA 0015 airfoil profile**, which offers a balanced trade-off between lift generation and structural strength for vertical axis applications.

Modeling Workflow

1. **Airfoil Profile Definition**: The NACA 0015 profile was imported as a base 2D section.
2. **Blade Geometry Construction**: The airfoil was extruded and lofted to form either straight or helically curved blades, depending on design optimization.
3. **Turbine Assembly**: The full turbine system was modeled, including the vertical shaft, support struts, hub, and base structure.
4. **Export for Simulation**: The completed model was exported in **STEP/IGES** formats to ensure compatibility with simulation environments (ANSYS Fluent and ANSYS Mechanical).

Design Considerations

- **Parametric Modeling**: Variables such as blade length, chord width, twist angle, and rotor radius were parametrized for flexibility in design iterations.
- **Structural Completeness**: The model incorporated all essential features such as **blade mounts**, **support struts**, and **hub geometry** to simulate real-world loading conditions accurately (Figure-1).

5.2 Mesh Generation and Boundary Conditions

The imported CAD geometry was processed using **ANSYS Meshing**, with an emphasis on grid quality and resolution to ensure accurate computational fluid dynamics (CFD) results (Figure-2).

Mesh Strategy

- **Mesh Type**: A combination of **unstructured tetrahedral elements** with localized **inflation layers** near blade surfaces was used.
- **Refinement Zones**:
    - Blade boundary layers
    - Wake region downstream of the turbine
    - Leading and trailing edges for high gradient capture

Boundary conditions

Domain Region	Boundary Type
Inlet	Velocity inlet (constant wind speed)
Outlet	Pressure outlet (0 Pa gauge)
Blade Surfaces	No-slip wall
Rotating Zone	Sliding mesh or Moving reference frame
Domain Walls	Symmetry or stationary wall

5.3 Computational Fluid Dynamics (CFD) Analysis

CFD simulations were carried out in **ANSYS Fluent** to evaluate the aerodynamic performance of the Savonius turbine under low-wind urban conditions. The simulation employed the **Reynolds-Averaged Navier-Stokes (RANS)** equations along with continuity and energy equations (Figure-3)

Solver Details

- **Turbulence Models Used**:
    - Standard **k-ε model** for baseline comparisons
    - **k-ω SST** model for capturing near-wall and separation dynamics more accurately
- **Simulation Type**: Both **steady-state** and **transient simulations** were performed to capture:
    - Dynamic stall
    - Wake vortex evolution
    - Unsteady pressure fluctuations

Key Output Parameters

- **Static Pressure Distribution**: Assessed on windward and leeward surfaces of each blade to evaluate aerodynamic torque.
- **Velocity Fields and Streamlines**: Visualized to understand flow acceleration, stagnation points, and wake turbulence.
- **Turbulence Intensity**: Mapped in the rotor wake to assess performance in turbulent conditions.
- **Vortex Shedding and Recirculation Zones**: Identified using Q-criterion or vorticity magnitude for dynamic analysis.

VI. RESULTS AND DISCUSSION

6.1 Material Selection Outcomes Using AHP

The objective of the material selection was to determine the most suitable candidate for

Savonius-type VAWT blades, operating in low-wind conditions (~2 m/s) with a target output of ~1 kW. The **Analytic Hierarchy Process (AHP)** was employed to evaluate five materials—**Steel, Aluminum, Fiberglass, Carbon Fiber, and HDPE**—across nine critical criteria: cost, toughness, corrosion resistance, density, Young's modulus, hardness, thermal conductivity, thermal capacity, and thermal expansion. **AISI 422 stainless steel** emerged as the most suitable material due to its consistent performance across critical mechanical and economic criteria. While composites offer advantages in weight and corrosion resistance, steel provides a better cost-to-performance ratio, especially for robust urban installations.

6.2 Structural Analysis Using FEA

Finite Element Analysis (FEA) was conducted in **ANSYS Mechanical** to evaluate the structural response of the selected blade design under wind loads. The model was meshed using **tetrahedral elements**, favored for their adaptability to complex geometries and support for **higher-order elements (SOLID187)**.

Boundary Conditions

- **Fixed Support** at blade base (simulating turbine hub connection)
- **Uniform Pressure Load** applied on the blade surface representing aerodynamic wind force

Key Structural Outputs

- **Directional Deformation**: Primarily along the wind direction, showing uniform deflection patterns, indicating proper load distribution.
- **Von Mises Stress**: Remained well within the material's yield strength, confirming the blade's structural integrity.
- **No stress concentration zones** or failure-prone regions were identified in the current design.

The simulations confirm that:

- **Material selection via AHP** successfully identified a cost-effective and mechanically robust candidate.
- **CFD results** demonstrated favorable aerodynamic characteristics suitable for urban wind conditions.
- **FEA outputs** verified the blade's structural performance under operational loading scenarios.

Overall, the proposed Savonius-type VAWT blade design meets the mechanical and aerodynamic requirements for low-wind, small-scale power generation. Its design is both **technically viable** and **economically feasible**, forming a strong basis for urban deployment.

VII. CONCLUSION

This study presented a comprehensive design and analysis framework for a **Savonius-type Vertical Axis Wind Turbine (VAWT)** aimed at **mini power generation** in **low-wind urban environments**, such as for powering traffic signals and decentralized micro-infrastructure. The core objective was to develop a blade system capable of generating approximately **1 kW of electrical power** at a low wind speed of **2 m/s**, leveraging aerodynamic efficiency, structural resilience, and material optimization.

To support this, a multi-criteria decision-making approach using the **Analytic Hierarchy Process (AHP)** was implemented to select the most suitable blade material among five candidates. Based on nine performance criteria—ranging from mechanical strength to thermal properties—**AISI 422 stainless steel** was identified as the optimal material, offering a balanced trade-off between cost, toughness, and environmental durability.

The blade geometry was modeled in **CATIA V5** and subjected to rigorous aerodynamic and structural simulation using **ANSYS Fluent** and **ANSYS Mechanical**. CFD results demonstrated stable airflow patterns and effective pressure differentials across the blade surfaces, validating aerodynamic performance under low-wind, turbulent conditions. Structural analysis using tetrahedral meshing confirmed that the blade design withstands operational loads with acceptable stress levels and minimal deformation, ensuring long-term reliability.

The integration of design simplicity, urban compatibility, and simulation-based validation underscores the **technical and economic feasibility** of the proposed VAWT configuration. Additionally, the project highlights key design strategies—including boundary layer refinement, material prioritization, and realistic flow modeling—that can inform future developments in small-scale renewable systems.

Future Scope

Building upon the validated design, future work may explore:

- **Hybrid systems** combining VAWT with solar PV
- **Use of advanced composites** or **3D-printed materials** for weight and efficiency optimization
- **IoT-based smart monitoring** for real-time performance tracking and predictive maintenance
- **Deployment in off-grid or rural electrification** projects

This study serves as a scalable model for sustainable, small-scale wind energy solutions adaptable to modern urban infrastructure.

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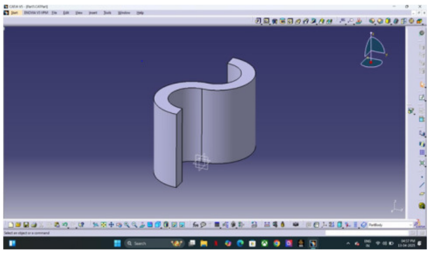

Figre-1

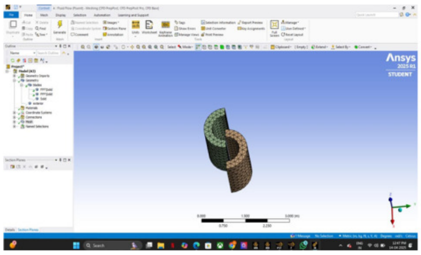

Figure-2

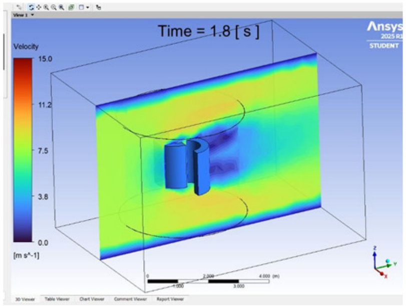

Figure-3