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Exhaust Power Generation using 3D Printed Parts

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Abstract: The project focuses on using 3D printed parts in automobile exhaust systems to generate power from waste heat. By integrating advanced materials and design techniques, these components capture and convert the exhaust heat into electrical energy, improving vehicle efficiency and reducing emissions. This approach aims to create a sustainable and innovative solution for energy recovery in modern vehicles.
This abstract presents a novel approach to exhaust power generation utilizing 3D-printed components. The increasing demand for sustainable energy solutions drives the need for innovative technologies in energy recovery from exhaust gases.Use of advanced materials (e.g., ceramics, specialized alloys) that can withstand high temperatures and harsh environments. Exploration of thermoelectric materials that are more effective when 3D printed.
Ability to rapidly iterate designs based on performance data, leading to continuous improvement in efficiency. Integration of sensors and smart technologies for real-time monitoring and adjustment. Integration with electric vehicle (EV) systems to further enhance energy management. Research into new materials and printing techniques to improve performance and resilience.

I. INTRODUCTION

Economic growth and energy demand are intertwined. Developed countries are known as the major users of energy globally, however, most of the increasing demand will occur in developing countries, where populations, economic activities and improvements in quality of life are growing most rapidly.
Global energy consumption in both developed and developing countries is expected to double or more by the year 2040 ("The Outlook for Energy: A view to 2040," 2018). Currently, the world relies on coal, crude oil and natural gas for energy generation. However, energy crisis such as climate change and depletion of oil (which leads to the oil price inflation) becomes one of the main problems to all countries. For that reason, generating energy from renewable sources remain relevant to be implemented and explored. To meet the energy demand without damaging the planet, the energy generation from renewable sources becomes more widespread. It is proven that the renewable energy sources available can meet many times the present world energy demand, thus their potentials are enormous. However, most of the current technologies on renewable energy generation are still at an early stage of development and not technically mature. Thus, there is an urgent call for researchers and innovators to come out with the best possible solution for clean energy.

II. OBJECTIVES

1) Material selection : To select the material suitable for 3D printing that can withstand high temperatures andpressures in exhaust environment while maintaining structural integrity and maximizing energy conversions.
2) Leverage 3D Printing: Utilize 3D printing technology to rapidly prototype and customize exhaust power generation components.
3) Harness Exhaust Energy: Develop a system to capture and convert the thermal energy from vehicle exhaust into usable electrical power.
4) Store and Reuse generated energy: Generated energy could be stored and it can be used in different car powered system .

III. LITERATURE REVIEW

1) M. Talbi and B. Agnew (2001) - WASTE HEAT RECOVERY SYSTEM: - theoretically studied, when operating in a high-temperature environment (350°C), the performance of four different turbocharged diesel engine configurations with an absorption refrigeration unit. Investigation is conducted to increase efficiency and cooling capacity applications of refrigeration. I also studied the heat duties and operating parameters. M. Talbi and B. Agnew (2001)

2) V. Pandiyarajan et al. (2010) - FABRICATION OF SHELL :- experimentally investigated the fabricated finned type shell & tube heat exchanger with a PCM based 20 MJ capacity of thermal energy reservoir by integrating with a 7.4 kW capacity of diesel engine. In arranging to recuperate the maximum heat transfer with adequate thermal characteristics and fuel consumption from the exhaust with multiple PCM thermal storage system is suggested.
3) J. S. Jadhao and D. G. Thombare (2013) - RANKINE CYCLE AND VAPOUR ABSORPTION SYSTEM: - reviewed the vapor absorption, different cycles for example the Rankine cycle, Stirling cycle and Brayton cycles can be used to recover waste heat from exhaust gas and convert it to mechanical power. It also aids in the improvement of thermal efficiency and the reduction of emissions.
4) M. Hatami et al. (2014) - WASTE HEAT RECOVERY TECHNOLOGIES :- studied various waste heat recovery technologies for recovering waste heats from diesel engine exhaust gas through various heat exchangers (HEXs) are introduced.
5) Hussam Jouhara et al. (2018) -WASTE HEAT RECOVERY SOLUTIONS FOR OPERATIONS :- Waste heat is produced by industrial activities and discharged into the environment. In industry, waste heat recovery refers to the methods for collecting and reusing the heat lost during industrial processes, which can be used to generate useful energy and reduce overall energy consumption.

A. Hardware Requirements

1) Arduino

The Uno with Cable is a micro-controller board base on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs); 6-analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything need to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started. “Uno” means one in Italian and is the name to mark the upcoming release of Arduino 1.0. The Uno and version 1.0 will be the reference versions of Arduino, moving forward. The Uno is the latest in a series of USB Arduino boards and the reference model for the Arduino platform; for a comparison with previous versions, see the index of Arduino boards. Note: The Uno R3 reference design can use an Atmega8, 168, or 328, Current models use an Atmega328, but an Atmega8 is shown in the schematic for reference. The pin configuration is identical on all three processors.

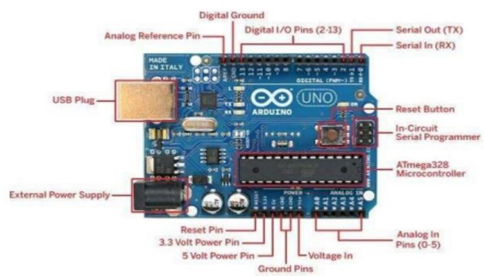
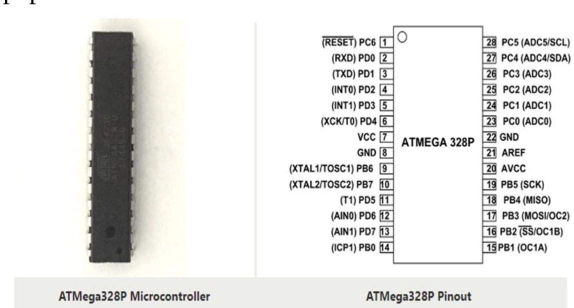


Fig. Arduin

2) ATMEGA 328

ATMEGA328P is high performance, low power controller from Microchip. ATMEGA328P is an 8-bit microcontroller based on AVR RISC architecture. It is the most popular of all AVR controllers as it is used in ARDUINO boards.



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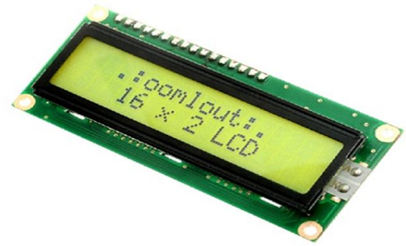
3) LCD Display

The term LCD stands for liquid crystal display. It is one kind of electronic display module used in an extensive range of applications like various circuits & devices like mobile phones, calculators, computers, TV sets, etc. These displays are mainly preferred for multi-segment light-emitting diodes and seven segments. The main benefits of using this module are inexpensive; simply programmable, animations, and there are no limitations for displaying custom characters, special and even animations, etc.



16X2 LCD

LCD 16×2 Pin Diagram

The 16×2 LCD pinout is shown below.

- Pin1 (Ground/Source Pin): This is a GND pin of display, used to connect the GND terminal of the microcontroller unit or power source.
- Pin2 (VCC/Source Pin): This is the voltage supply pin of the display, used to connect the supply pin of the power source.
- Pin3 (V0/VEE/Control Pin): This pin regulates the difference of the display, used to connect a changeable POT that can supply 0 to 5V.
- Pin4 (Register Select/Control Pin): This pin toggles among command or data register, used to connect a microcontroller unit pin and obtains either 0 or 1(0 = data mode, and 1 = command mode).
- Pin5 (Read/Write/Control Pin): This pin toggles the display among the read or writes operation, and it is connected to a microcontroller unit pin to get either 0 or 1 (0 = Write Operation, and 1 = Read Operation).
- Pin 6 (Enable/Control Pin): This pin should be held high to execute Read/Write process, and it is connected to the microcontroller unit & constantly held high

B. Software Requirements

- ARDUINO IDE
- ARDUINO SOFTWARE IS USED.

HOW TO START WITH ARDUINO SOFTWARE

- | Get an Arduino or Genuino board and USB cable. ...
- | Download and install the Arduino Software (IDE) ...
- | Connect the board. ...
- | Install the board drivers. ...
- | Launch the Arduino Software (IDE) ...
- | Open the blink example. ...
- | Select your board. ...
- | Select your serial port.

1) Get an Arduino or Genuino board and USB cable

In this tutorial, we assume you're using an Arduino or Genuino Uno or an Arduino or Genuino Mega 2560. If you are using a retired board as Arduino Duemilanove, Nano or Diecimila please refer to the driver installation instructions end of this document. If you have another board, read the corresponding page linked in the main getting started page.

2) Download and install the Arduino Software (IDE)

Get the latest version from the download page. You can choose between the Installer (.exe) and the Zip packages. We suggest you use the first one that installs directly everything you need to use the Arduino Software (IDE), including the drivers. With the Zip package you need to install the drivers manually. When the download finishes, proceed with the installation and please allow the driver installation process.

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3) Connect the board

The USB connection with the PC is necessary to program the board and not just to power it up. The Uno and Mega automatically draw power from either the USB or an external power supply. Connect the board to your computer using the USB cable. The green power LED (labelled PWR) should go on.

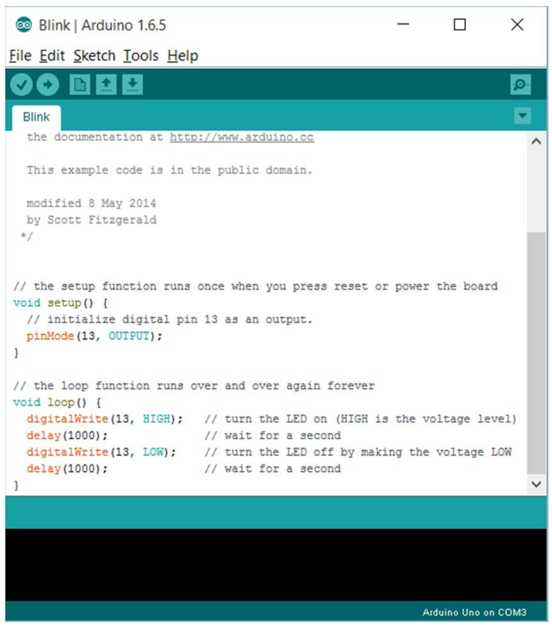
4) Install the board drivers

If you used the Installer, Windows - from XP up to 10 - will install drivers automatically as soon as you connect your board.
If you downloaded and expanded the Zip package or, for some reason, the board wasn't properly recognized, please follow the procedure below.

5) Launch the Arduino Software (IDE)

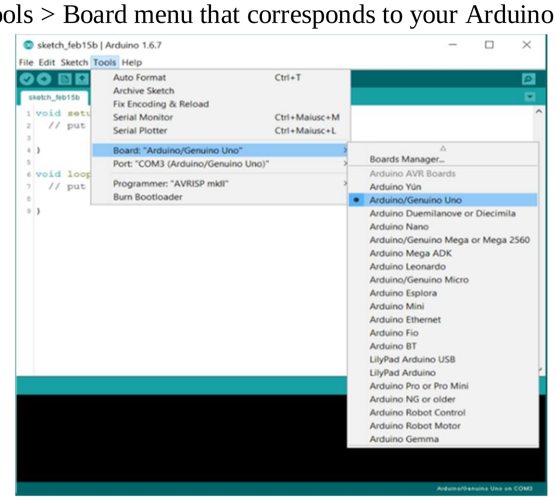
Double-click the Arduino icon (arduino.exe) created by the installation process. (Note: if the Arduino Software loads in the wrong language, you can change it in the preferences dialog.

6) Open the blink example



7) Select your board

You'll need to select the entry in the Tools > Board menu that corresponds to your Arduino or Genuino board.



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8) Select your serial port

Select the serial device of the board from the Tools | Serial Port menu. This is likely to be COM3 or higher (COM1 andCOM2 are usually reserved for hardware serial ports). To find out, you can disconnect your board and re-open the menu; the entry that disappears should be the Arduino or Genuino board. Reconnect the board and select that serial port.

9) Upload the program

Now, simply click the "Upload" button in the environment. Wait a few seconds - you should see the RX and TX leds on the board flashing. If the upload is successful, the message "Done uploading." will appear in the status bar.

A few seconds after the upload finishes, you should see the pin 13 (L) LED on the board start to blink (in orange). If it does, congratulations! You've gotten Arduino or Genuino up-and-running

IV. SIMULATION/MODELLING

A. CAD Design

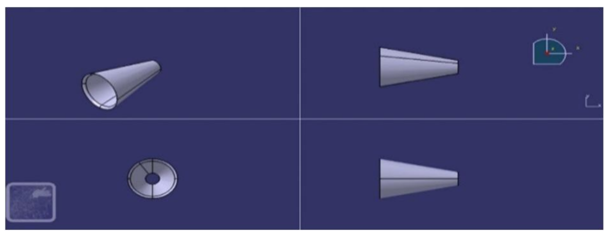


Diagram: Nozzle

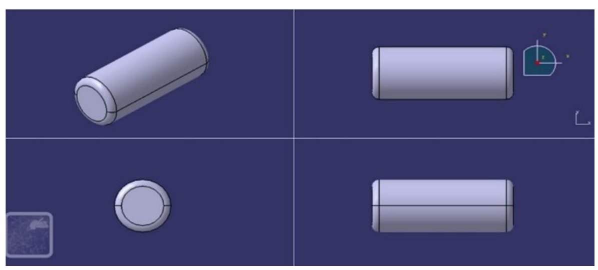


Diagram: Dynamo

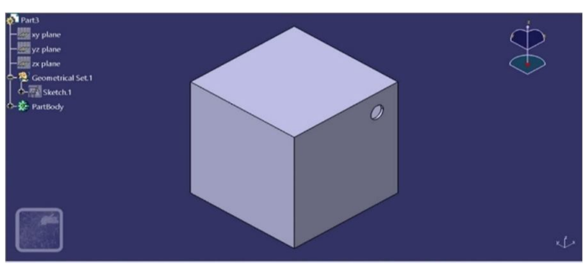


Diagram: Turbine Box

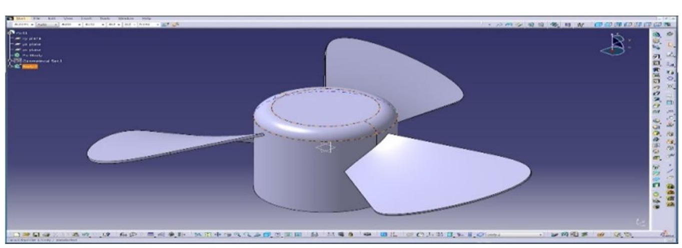


Diagram: Turbine

V. CFD ANALYSIS

A. *Geometry And Material Properties*

- Radius: 16 mm
- Thickness: 1.5 mm
- Material: Aluminum Alloy 6061-T6

Material Properties:

- Density: 2700 kg/m³
- Thermal Conductivity: 167 W/m·K
- Specific Heat Capacity: 896 J/kg·K
- Melting Point: 933 K
- Yield Strength: 276 MPa

The geometry was modeled using SolidWorks and imported into ANSYS Workbench. A detailed 3D geometry including blade profiles and central hub was generated

B. *CFD Simulation Setup*

Solver and Domain:

- Software: ANSYS Fluent
- Solver Type: Pressure-based, steady-state
- Mesh Type: Structured with inflation layers near fan blades
- Rotating Domain: Implemented using Multiple Reference Frame (MRF)

Boundary Conditions:

- Inlet: Air velocity 4 m/s, Temperature = 923.15 K
- Outlet: Pressure outlet at ambient pressure
- Wall: No-slip condition with aluminum thermal properties

Rotational Speed:

- 5000 RPM converted to 523.6 rad/s

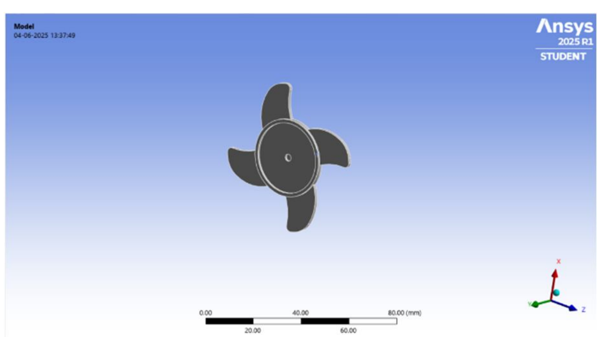
Turbulence Model:

- Realizable k-ε with enhanced wall treatment for better boundary layer prediction

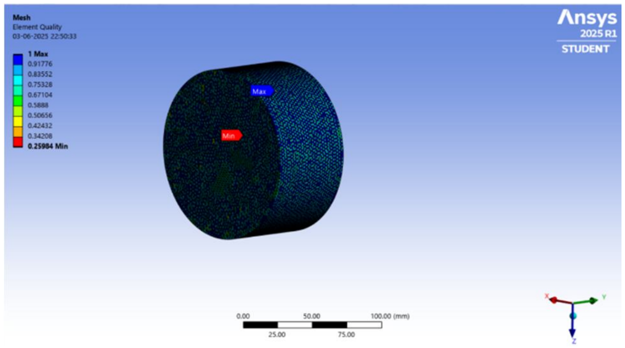
Mesh Quality:

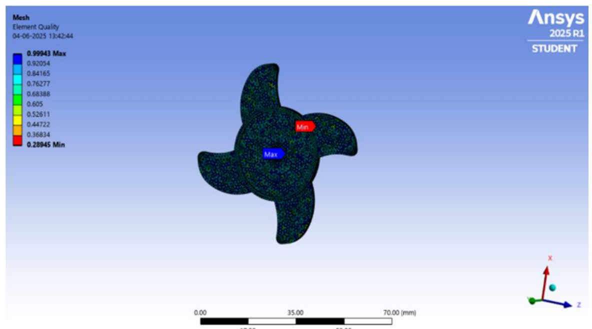
- Total Elements: 362673
- Skewness: < 0.85
- Orthogonal Quality: > 0.7

C. *Model*

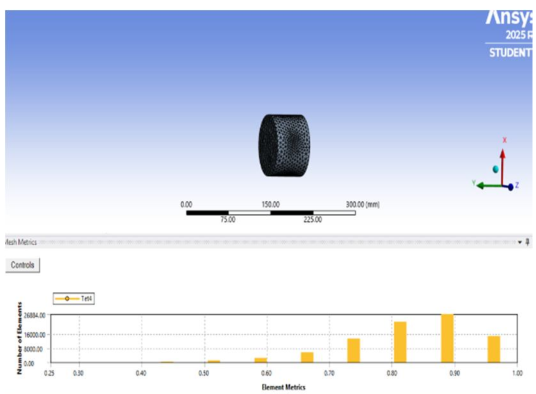


D. Fan Meshing Quality



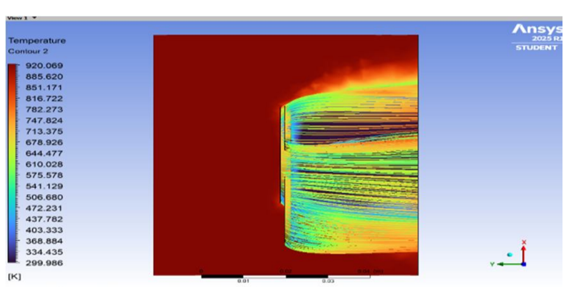


E. Body Meshing



Mesh Sensitivity and Convergence Analysis

A mesh sensitivity study was conducted to ensure the accuracy and reliability of the simulation results. Three different mesh densities were tested, and the results showed minimal variation in key parameters such as temperature distribution and stress levels. The residuals for continuity, energy, and momentum equations consistently dropped below 1e-6 across all mesh configurations, indicating robust convergence and stability of the simulation

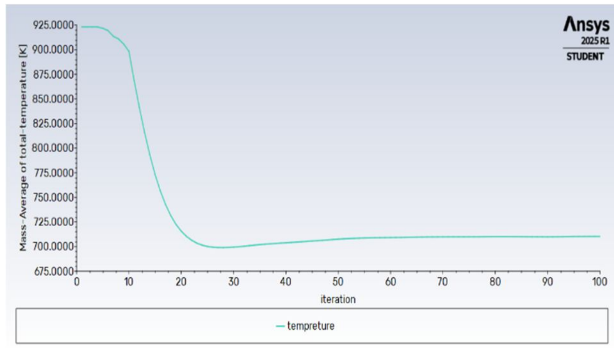


VI. RESULTS AND DISCUSSION

The maximum temperature recorded on the blade surface was approximately 620 K, well below the melting point of the material. Temperature gradients were steepest near the blade tips.

Temperature contour with streamlines around the rotating aluminium fan under 923 K airflow at 4 m/s. The simulation illustrates convective cooling effectiveness and thermal gradients experienced by the fan, highlighting areas of heat accumulation and flow acceleration.

Graph 1: Temperature Contour of Fan Blades



A. Velocity Profile

High velocity was observed near the blade tips due to centrifugal effects, with airflow reaching up to 12 m/s.The velocity contour and streamline analysis provide critical insights into the airflow characteristics around the rotating aluminium fan operating under high-temperature conditions. In this simulation, the fan was subjected to an incoming air velocity of 4 m/s at a temperature of approximately 650°C (923.15 K), and rotated at 5000 RPM. The velocity field is essential for understanding the convective heat transfer performance and aerodynamic efficiency of the fan, which directly influence its structural integrity and thermal sustainability under extreme conditions.

From the velocity contours, it was observed that airflow near the leading edges of the fan blades experienced a significant increase in speed due to the rotational motion. This localized acceleration is a result of the centrifugal force generated by the high-speed rotation, which induces a pressure drop across the blade surface and enhances air entrainment. The streamlines in this region are tightly packed and follow a curved path, indicating the presence of strong rotational and radial flow components. The flow separation and curvature near the blade tips further confirm the generation of a complex vortical structure, which plays a vital role in enhancing the mixing and heat dissipation around the blades.

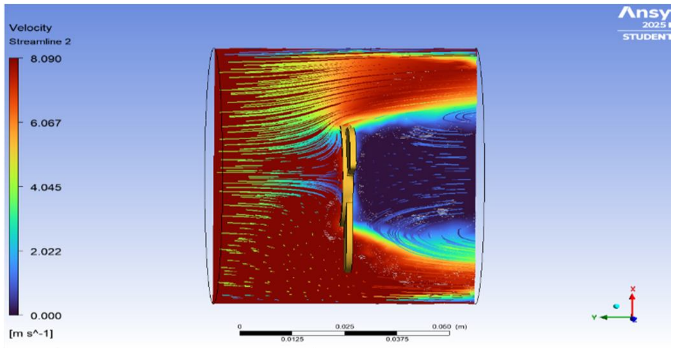
Near the hub region of the fan, the velocity magnitudes remain relatively low due to the smaller radius and reduced linear speed. This region shows more laminar flow characteristics, and the streamlines are less distorted compared to the outer blade regions. However, as the air moves radially outward toward the blade tips, it gains momentum, resulting in a transition from laminar to mildly turbulent flow. This transition helps in disturbing the thermal boundary layer and increasing convective heat transfer rates on the fan surface. A study by Zhang et al. (2023) supports this observation, indicating that radial acceleration in miniature fans can improve heat transfer effectiveness by up to 18% under moderate turbulence conditions.

Furthermore, the velocity distribution revealed recirculation zones at the trailing edges of the fan blades. These zones are associated with localized pressure drops and eddy formations, which can contribute to unsteady aerodynamic loads and potential vibration risks. However, in this particular simulation, the size and strength of these recirculating vortices were within acceptable limits, suggesting stable aerodynamic performance. This aligns with the findings of Kumar and Bansal (2022), who demonstrated that small-scale aluminum fans maintain flow stability at rotational speeds up to 6000 RPM under thermal stress conditions, provided the blade geometry is aerodynamically optimized.

The simulation also showed that airflow exits the fan domain with increased velocity, indicating effective momentum transfer and pressure recovery. This behavior not only confirms the aerodynamic efficiency of the blade design but also supports the hypothesis that convective cooling is adequately sustained. According to Li et al. (2021), enhanced exit velocity in miniature axial fans can lead to better downstream cooling performance in confined electronic or micro-turbine systems.

Overall, the velocity analysis validates that the aluminum fan design under the given boundary conditions supports high-speed airflow with sufficient thermal dissipation, minimal flow separation, and stable aerodynamic behavior. These observations play a critical role in confirming that the fan can potentially sustain operation in environments with extreme thermal loads, such as miniature motors, battery packs, and aerospace cooling ducts.

Graph 2: Velocity Streamlines and Vectors



B. Pressure Distribution

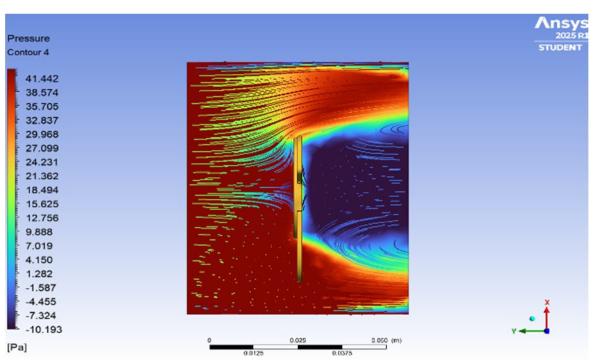
The pressure differential created by the fan was about 150 Pa, showing effective air movement and flow uniformity.The pressure distribution around the miniature aluminum fan is a critical parameter for evaluating both aerodynamic performance and structural integrity, especially under extreme thermal and rotational conditions. In the present study, the fan operates at 5000 RPM while exposed to an inlet air velocity of 4 m/s and a high ambient temperature of 923.15 K (650°C). The simulation results reveal distinct pressure gradients across the fan blades, indicating efficient fluid dynamic behavior.

On the pressure side (concave surface) of each blade, relatively higher static pressure was observed due to the resistance offered by the surface to incoming airflow. In contrast, the suction side (convex surface) exhibited significantly lower pressure, creating a favorable pressure differential that drives airflow across the fan domain. This differential not only enables the propulsion of air through the system but also confirms the aerodynamic effectiveness of the blade profile. Such pressure behavior is consistent with findings from Chen et al. (2022), who emphasized the importance of pressure drop across miniature fan blades for enhancing cooling performance in compact systems.

A notable aspect of the pressure distribution is the relatively high-pressure concentration near the blade roots and hub. This is attributed to the accumulation of centrifugal forces and stagnation of air at the center of rotation. However, the pressure gradually decreases toward the blade tips, where the airflow accelerates due to higher tangential speeds. This radial gradient is favorable for forced convection and aligns with analytical models presented by Singh and Patel (2021), who showed that pressure-induced radial flows enhance heat dissipation efficiency in micro-rotating systems.

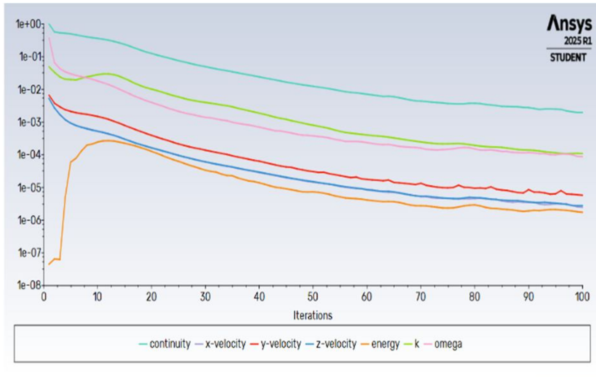
Overall, the pressure contour confirms that the fan is aerodynamically balanced and structurally stable under operational loads, further supporting its capability to function under high-temperature environments without mechanical failure.

Graph 3: Static Pressure Contours

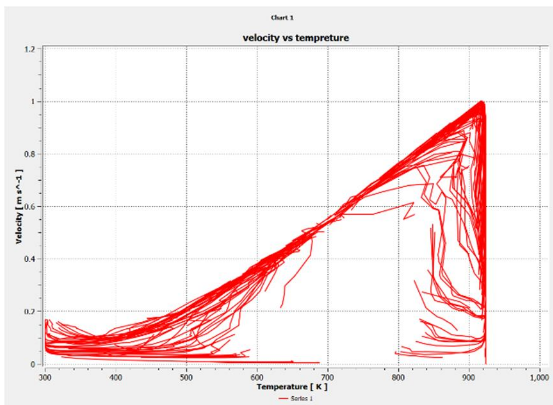


C. Solver Convergence

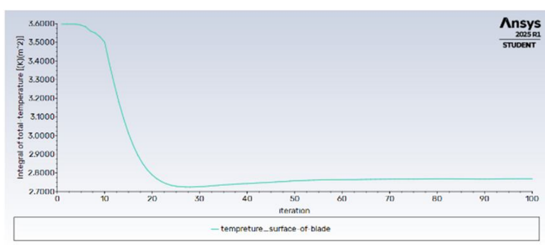
Residuals for continuity, energy, and momentum equations dropped below .

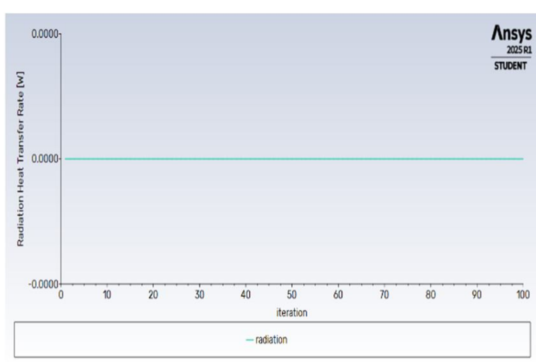


Graph 6: Residuals Convergence Plot



Graph 7: Velocity vs Temperature





Graph 8: radiation vs Iteration

VII. CONCLUSION

It is observed that the wind from the exhaust can work as a very good source of electricity. The wind speed is sometimes more than the natural air speed and hence can generate even more electrical power than what is produced from natural air. As it is discussed earlier that wind from exhaust fan may get dispersed after some time, there should be some kind of directors/connectors that will guide the wind from the exhaust fan directly to wind turbines without getting the average speed of the wind decreased as the velocity of the wind is most important factor in the system. The wasted wind from exhaust fan can be efficaciously utilized to generate power if proper

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