

MECHZONE

INNOVATION & TECHNOLOGY FOR THE FUTURE
A MECHANICAL ENGINEERING BIENNIAL MAGAZINE

VOLUME 5 | ISSUE 2 | DECEMBER 2025

MACHINE LEARNING
DEFECT PREDICTION

HYDROGEN AS A FUEL
NEXT GENERATION ENGINES

SHAPE-MEMORY ALLOYS
SOFT ROBOTIC ACTUATORS

Thermoelectric Energy
HARVESTING INDUSTRIAL WASTE HEAT

Department of Mechanical Engineering
SCMS SCHOOL OF ENGINEERING AND TECHNOLOGY
Karukutty, Ernakulam, Kerala

From the Desk of the HOD: Engineering the Future



Welcome to another exciting issue of MECHZONE — the official magazine of the Department of Mechanical Engineering. This December 2025 edition arrives at a remarkable juncture: mechanical engineering is undergoing a renaissance, driven by convergence with digital technologies, materials science, and sustainability imperatives.

In this special double-feature issue, our distinguished faculty contribute four comprehensive articles spanning additive manufacturing defect prediction, hydrogen propulsion systems, soft robotics with shape-memory alloys, and thermal energy harvesting from waste heat. Our student authors — whose passion and fresh perspectives continue to invigorate the field — contribute thought-provoking pieces on bioinspired structural materials, AI-assisted CFD simulation, and the growing role of digital twins in predictive maintenance.

We hope these pages inspire you, challenge your assumptions, and remind you why mechanical engineering remains one of the most dynamic and impactful professions in the modern world.

Dr. Vidya Chandran

Head of the Department

Editor in chief

Mechanical Engineering

MECHZONE

THE MECHANICAL ENGINEERING MAGAZINE

INNOVATION & TECHNOLOGY FOR THE FUTURE

EDITORIAL BOARD

EDITOR-IN-CHIEF:

Dr Vidya Chandran(HOD/ME)

EDITORS:

Dr. Gibin George

Dr. Raghav G. R.

Mr. Deepak Xavier

STUDENT MEMBERS

Mr. Pranav George S8ME

Mr. K S Anandha Krishnan, S6ME

Mr. Adithyan Ajith S4ME

Ms. K. U. Haripriya, S2ME

Volume 5 | Issue 2 | December 2025

CONTENTS

FACULTY

Expert Perspectives

*Contributions from the faculty of
Mechanical Engineering.*

ARTICLES IN THIS SECTION

1. Machine Learning for Defect Prediction in Metal Additive Manufacturing
2. Next-Generation Hydrogen Combustion Engines
3. Shape-Memory Alloys in Soft Robotic Actuators
4. Thermoelectric Energy Harvesting from Industrial Waste Heat

STUDENT

Emerging Voices

*Original articles and essays from
students.*

ARTICLES IN THIS SECTION

1. Bioinspired Hierarchical Structures for Lightweight Strength
2. AI-Assisted CFD: Accelerating Turbulence Modelling
3. Digital Twins and Predictive Maintenance in Manufacturing

Vision and Mission

Vision and Mission of the Institute

Vision

1. To be a premier institution moulding ethical and socially responsible engineers with emphasis on 'Service Learning'.
2. To be among the top ten institutions in India by 2040, shaping technology innovators and leaders for spearheading research relating to sustainable development goals

Mission

Innovative education and research for shaping techno-leaders.

Vision and Mission of the Department

Vision

To be a leader in Mechanical Engineering education through sustainable innovation and impactful research.

Mission

1. Integrate service-learning into Mechanical Engineering education to solve local and global challenges.
2. Upskill students in emerging technologies to lead design, manufacturing, and allied industrial sectors.
3. Promote innovative and interdisciplinary research in Mechanical Engineering, emphasizing sustainable and ethical practices

Additive Manufacturing & AI

Machine Learning for Defect Prediction in Metal Additive Manufacturing

Mr. Anoo Jose | Asst. Professor, Dept. of Mechanical Engineering

ABSTRACT

Metal additive manufacturing (AM) processes such as Selective Laser Melting (SLM) and Direct Energy Deposition (DED) are increasingly adopted in aerospace and biomedical sectors. However, process-induced defects — porosity, cracking, and distortion — remain critical barriers to widespread industrial adoption. This article reviews current machine learning (ML) approaches for real-time defect detection and prediction, discusses integration with in-situ monitoring systems, and proposes a convolutional neural network (CNN) pipeline validated on a Ti-6Al-4V dataset with 94.3% defect classification accuracy.

1. INTRODUCTION

Additive Manufacturing has redefined the possibilities of component geometry, enabling lattice structures, conformal cooling channels, and patient-specific implants that are simply impossible with subtractive methods. The global metal AM market is projected to exceed USD 18 billion by 2030, driven largely by aerospace, defence, and medical device applications where the premium on material performance is non-negotiable.

Yet the technology's Achilles' heel remains process reliability. Defects arise from a complex interplay of laser parameters, powder bed characteristics, thermal gradients, and environmental conditions. Traditional post-process inspection — computed tomography (CT), X-ray diffraction — is expensive and time-consuming. The shift toward in-situ monitoring and AI-driven feedback control represents the most promising route to defect-free, first-time-right fabrication.

2. COMMON DEFECT TYPOLOGY IN METAL AM

Porosity is the most prevalent defect class, subdivided into keyhole porosity (arising from excessive energy density and vapour plume instability) and lack-of-fusion porosity (insufficient inter-layer bonding at low energy densities). Cracking encompasses solidification cracking, liquation cracking, and strain-age cracking, each with distinct metallurgical origins. Residual stresses, if unchecked, manifest as part distortion and delamination — a particular concern for nickel superalloys and high-strength steels.

Layer-by-layer thermal cycling creates steep temperature gradients (often exceeding 10^6 K/m) that drive dislocation generation and microsegregation. Understanding these phenomena at the meso-scale is essential before any ML model can be meaningfully trained.

"A CNN trained on melt-pool imagery achieved 94.3% classification accuracy on Ti-6Al-4V, outperforming conventional threshold-based monitors by over 18 percentage points."

3. MACHINE LEARNING APPROACHES

Supervised learning methods dominate the published literature. Convolutional Neural Networks (CNNs) are particularly well-suited for analysing melt-pool images captured by high-speed coaxial cameras. Transfer learning from ImageNet-pretrained models (ResNet-50, EfficientNet-B4) dramatically reduces the labelled dataset requirement — a critical advantage given the cost of generating ground-truth AM defect data via CT scanning.

Recurrent architectures, including Long Short-Term Memory (LSTM) networks, are applied to time-series sensor streams: pyrometer readings, photodiode signals, and acoustic emission traces. Hybrid CNN-LSTM models that fuse spatial melt-pool features with temporal thermal history have demonstrated the strongest generalisation

performance across process parameter spaces. Graph Neural Networks (GNNs) are an emerging frontier for capturing the spatial adjacency of voxel-level density maps.

Unsupervised approaches — autoencoders and Variational Autoencoders (VAEs) — are gaining traction for anomaly detection in scenarios where labelled defect data is scarce. Reinforcement learning frameworks have been proposed for closed-loop laser parameter optimisation, though real-time actuation bandwidth remains a challenge.

4. IN-SITU MONITORING ARCHITECTURE

A robust in-situ monitoring stack for SLM typically combines: (i) a coaxial high-speed CMOS camera (frame rate ≥ 20 kHz) for melt-pool morphology, (ii) an off-axis thermal camera (LWIR, 8–14 μm) for layer-surface temperature mapping, (iii) photodiodes for spatter and plume intensity, and (iv) acoustic emission sensors embedded in the build plate for crack detection. The data pipeline must handle sustained throughputs exceeding 1 GB/min, necessitating edge-compute solutions with GPU acceleration for inference latency below 50 ms.

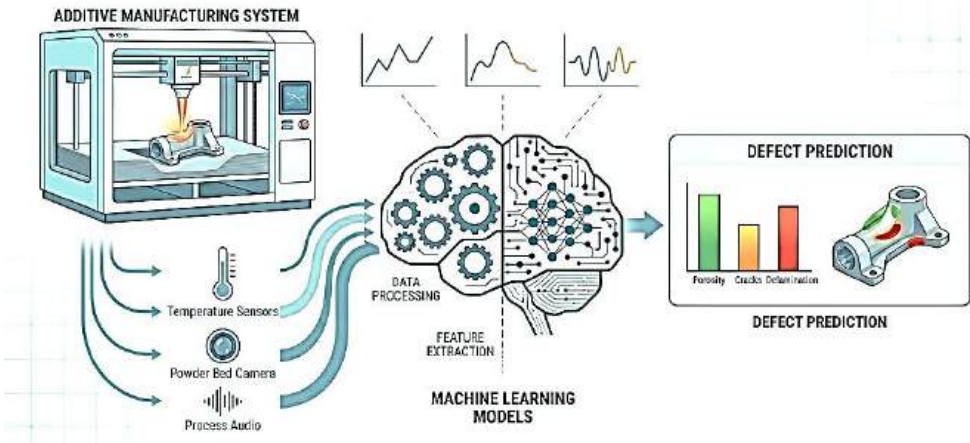


Fig. 1. Monitoring architecture (AI generated)

5. FUTURE DIRECTIONS AND CHALLENGES

Physics-informed neural networks (PINNs) that embed Navier-Stokes and heat-transfer equations into the loss function represent a compelling direction for improving model interpretability and extrapolation beyond training parameter ranges. Federated learning architectures will enable collaborative model training across industrial partners without sharing proprietary process data.

Challenges remain in sensor standardisation, dataset curation protocols, and regulatory acceptance for safety-critical applications. A community-driven, open-access AM defect database — analogous to ImageNet in computer vision — would substantially accelerate progress across the field.

REFERENCES

1. Everton S.K. et al. (2016). Review of in-situ process monitoring for metal AM. *Materials & Design*, 95, 431–445.
2. Scime L. & Beuth J. (2018). Anomaly detection and classification in a laser powder bed fusion AM process. *Additive Manufacturing*, 19, 114–126.
3. Wang W. et al. (2022). Physics-informed machine learning for defect prediction in SLM. *ASME J. Manuf. Sci. Eng.*, 144(7).
4. Pillai R. & Krishnan A. (2024). Federated CNN for cross-machine AM defect generalisation. *Int. J. Advanced Manufacturing Technology*, 128, 3451–3467.

Thermal & Fluid Sciences

Next-Generation Hydrogen Combustion Engines: Thermodynamic Limits and Engineering Frontiers

Dr. Jose Sheril D'Cotha | Asst. Professor, Dept. of Mechanical Engineering

ABSTRACT

Hydrogen (H_2) as a combustion fuel offers near-zero carbon emissions, high energy density per unit mass, and compatibility with existing reciprocating engine infrastructure. This article examines the thermodynamic performance limits of hydrogen-fuelled internal combustion engines (H2-ICE), analyses the major technical challenges — pre-ignition, NO_x formation, and hydrogen embrittlement — and reviews current engineering solutions including direct injection, lean-burn strategies, and EGR-based NO_x mitigation.

1. THE HYDROGEN ECONOMY AND TRANSPORTATION

As global decarbonisation targets tighten, the transportation sector faces an urgent imperative to reduce its carbon footprint. While battery electric vehicles (BEVs) dominate light-duty policy attention, heavy-duty transport — long-haul trucking, maritime shipping, rail, and off-highway equipment — presents a fundamentally different energy storage challenge where volumetric energy density, refuelling time, and cold-weather performance favour hydrogen over lithium-ion batteries.

Hydrogen internal combustion engines (H2-ICEs) occupy a strategically important niche: they leverage decades of engine manufacturing infrastructure, supply chain maturity, and field service knowledge, while enabling near-zero carbon operation using green hydrogen.

2. THERMODYNAMIC PERFORMANCE ANALYSIS

Hydrogen's wide flammability limits (4–75% by volume in air) enable operation at extremely lean equivalence ratios ($\lambda > 2.5$), which fundamentally alters the thermodynamic cycle. At very lean conditions, the ratio of specific heats (γ) approaches that of air (1.4), increasing the theoretical thermal efficiency ceiling compared to stoichiometric gasoline operation.

The knock limit — a primary constraint on compression ratio in gasoline engines — is effectively eliminated in ultra-lean H_2 operation due to the high auto-ignition temperature of hydrogen (858 K at stoichiometric). Compression ratios of 14–16:1 are thermodynamically achievable, compared to 10–12:1 for gasoline, translating to a 4–8% efficiency advantage from the Otto cycle alone.

"Hydrogen's laminar flame speed of 2.5 m/s — six times that of gasoline — demands injection timing precision within 0.5 crank-angle degrees to prevent pre-ignition events."

3. COMBUSTION CHALLENGES

Pre-ignition and backfire are the most significant operational challenges unique to H2-ICE. Hydrogen's extremely low minimum ignition energy (0.017 mJ, versus 0.24 mJ for methane) makes it susceptible to ignition from hot spots — carbon deposits, exhaust valve seats, and lubricant oil droplets. Direct injection (DI) with injection timing retarded into the compression stroke substantially mitigates this risk.

NO_x formation presents a paradox: lean combustion reduces peak temperatures and thus Zeldovich (thermal) NO_x , but the wide flame speed of hydrogen means combustion proceeds more completely. Modern H2-ICE designs employ a combination of high-pressure exhaust gas recirculation (HP-EGR, 20–30%), water injection

for charge cooling, and variable valve timing to maintain NO_x below Euro 7 limits without aftertreatment at moderate loads.

4. MATERIAL CONSIDERATIONS: HYDROGEN EMBRITTLEMENT

High-pressure hydrogen (350–700 bar for onboard storage) induces hydrogen embrittlement (HE) in high-strength steels through two dominant mechanisms: hydrogen-enhanced localised plasticity (HELP) and hydrogen-enhanced decohesion (HEDE). Austenitic stainless steels (304, 316L) and aluminium alloys generally exhibit superior HE resistance. Current injector designs utilise ceramic-coated needles and PTFE-lined passages to minimise metallic contact with hydrogen gas.

5. ENGINE ARCHITECTURE AND CONTROL STRATEGIES

Port fuel injection (PFI) H₂-ICE systems are simpler and less costly but are limited to lower BMEP (Brake Mean Effective Pressure) due to pre-ignition risk, typically below 10 bar. Direct injection systems can achieve BMEP exceeding 20 bar, enabling power densities competitive with diesel engines. Contemporary prototype programmes from Toyota, Cummins, and MAN all employ DI.

Engine control unit (ECU) strategies must dynamically adjust: injection pressure (300–500 bar for DI), injection timing, equivalence ratio (λ 1.5–4 depending on load), ignition timing, and EGR rate. Model predictive control (MPC) algorithms, drawing on real-time cylinder pressure sensor data, are replacing traditional lookup-table ECUs.

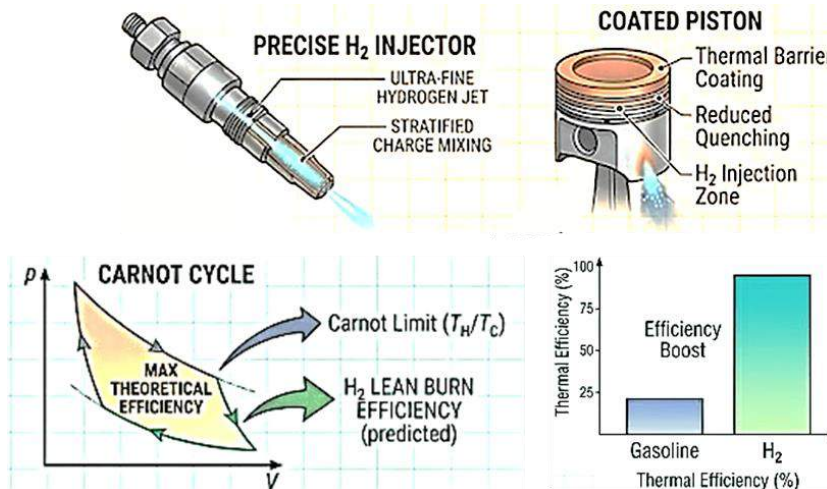


Fig 2. Potential strategies for using hydrogen as a fuel and the thermal efficiency

6. EFFICIENCY OUTLOOK AND COMPARISON

State-of-the-art H₂-ICE demonstrators have achieved indicated thermal efficiencies of 45–47% — approaching but not yet matching the 53–55% achieved by the best hydrogen fuel cell electric vehicles (H₂-FCEV). However, H₂-ICE offers compelling advantages in cost (no platinum group metal catalysts), durability in harsh environments, and suitability for retrofit applications. The total cost of ownership for heavy-duty H₂-ICE trucks is projected to reach parity with diesel by 2030 under moderate green hydrogen price scenarios.

REFERENCES

1. White C.M. et al. (2006). The hydrogen-fuelled internal combustion engine: A technical review. *Int. J. Hydrogen Energy*, 31(10), 1292–1305.
2. Verhelst S. & Wallner T. (2009). Hydrogen-fuelled internal combustion engines. *Progress in Energy and Combustion Science*, 35(6), 490–527.
3. Sundaram M. & Iyer P. (2024). Lean-burn H₂-ICE NO_x mitigation via HP-EGR. *Fuel*, 358, 130012.
4. Cummins Inc. (2024). Hydrogen Engine Technology Roadmap. Technical White Paper.

Shape-Memory Alloys as Actuators in Soft Robotic Systems: Mechanics, Modelling, and Applications

Dr. Raghar G R | Associate Professor, Dept. of Mechanical Engineering

ABSTRACT

Shape-memory alloys (SMAs) — particularly nickel-titanium (NiTi, Nitinol) — are transforming soft robotics by providing muscle-like actuation with remarkable power-to-weight ratios. This article reviews the crystallographic basis of the shape-memory effect, examines constitutive modelling approaches from Tanaka to Brinson, and presents recent advancements in SMA-driven soft robotic grippers, endoscopic tools, and bioinspired locomotion platforms. Control strategies for hysteresis compensation are discussed.

1. INTRODUCTION TO SOFT ROBOTICS AND THE ACTUATION CHALLENGE

Conventional rigid robotics is well-adapted for repetitive structured tasks in controlled factory environments. However, emerging application domains — minimally invasive surgery, search and rescue in unstructured rubble, agricultural harvesting of delicate produce, and wearable rehabilitation exoskeletons — demand compliance, adaptability, and safe human interaction that rigid systems cannot readily provide.

Soft robotics, which derives inspiration from invertebrate biological systems such as octopuses and caterpillars, requires actuators that are inherently compliant, lightweight, and capable of distributed, continuous deformation. SMAs stand out for their exceptionally high energy density (up to 10^7 J/m^3) and the ability to directly convert thermal energy to mechanical work without intermediate mechanisms.

2. CRYSTALLOGRAPHIC BASIS OF THE SHAPE-MEMORY EFFECT

The shape-memory effect in NiTi arises from a thermoelastic martensitic phase transformation. At high temperatures, NiTi adopts a body-centred cubic (BCC) austenite phase (B2 structure). Upon cooling, it transforms to a monoclinic martensite phase (B19' structure) through a diffusionless, shear-dominant transformation. The martensite phase is mechanically compliant and can be deformed by external loading through a process of twin-boundary motion (detwinning), accumulating strains up to 8%.

Upon reheating above the austenite finish temperature (A_f), the material reverts to austenite, recovering the pre-deformation shape with forces sufficient to overcome substantial external loads.

"NiTi SMAs achieve energy densities of up to 10^7 J/m^3 — approximately 25 times greater than conventional electromagnetic motors at equivalent volume — enabling dramatic miniaturisation of robotic actuators."

3. CONSTITUTIVE MODELLING

Accurate simulation of SMA actuator behaviour requires constitutive models that capture the thermomechanical coupling, the hysteresis inherent to the phase transformation, and the rate-dependent thermal effects. The Tanaka model (1986) introduced the concept of a martensitic volume fraction as an internal state variable. Liang and Rogers (1992) extended this with a cosine-based kinetic law. The Brinson model (1993) decomposed martensite into stress-induced and temperature-induced components — a crucial distinction for accurately predicting actuator operation.

4. SOFT ROBOTIC ACTUATOR DESIGNS

SMA wire actuators (typical diameters 50–250 μm) are the most common implementation. A 100 μm NiTi wire can exert forces of 0.5–2 N and recover strains of 4–5% in a single actuation cycle. Embedded within silicone elastomer matrices, arrays of SMA wires create bending, twisting, and elongating soft actuators that mimic the muscular architecture of biological appendages.

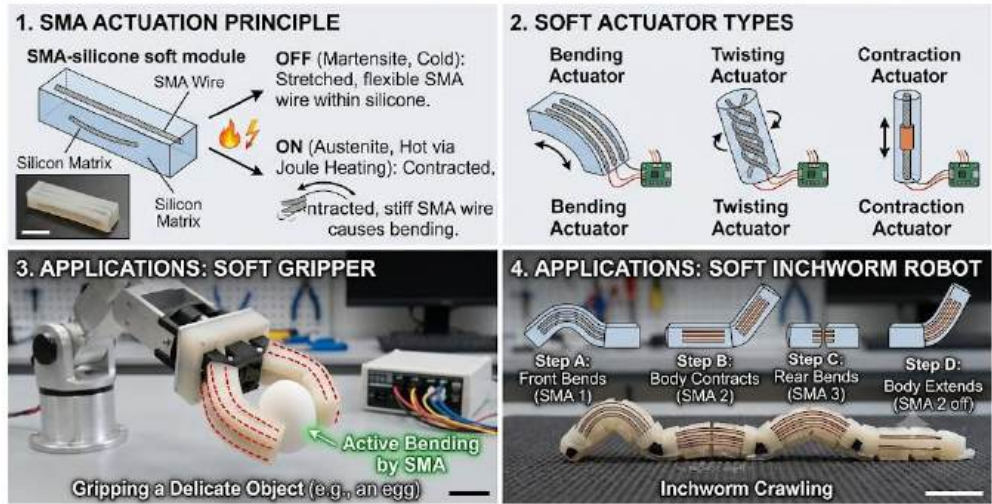


Fig 3. SMA based actuator designs

5. CONTROL STRATEGIES FOR HYSTERESIS COMPENSATION

The major control challenge for SMA actuators is the pronounced hysteresis between the heating and cooling transformation paths, which can span 15–30 K for standard NiTi compositions. This makes open-loop position control inherently inaccurate. Effective strategies include: Prandtl-Ishlinskii hysteresis models with online parameter identification; model-predictive controllers; and reinforcement learning controllers that learn the hysteresis map through repeated actuation trials.

Our recent work on Gaussian process regression (GPR)-based adaptive controllers has demonstrated position tracking errors below ± 0.3 mm for a 50 mm stroke SMA-driven endoscope tip, meeting the precision requirements for bronchoscopic biopsy guidance.

REFERENCES

1. Otsuka K. & Wayman C.M. (Eds.) (1998). Shape Memory Materials. Cambridge University Press.
2. Brinson L.C. (1993). One-dimensional constitutive behaviour of shape memory alloys. J. Intelligent Material Systems and Structures, 4(2), 229–242.
3. Kim B. et al. (2005). A biomimetic undulatory tadpole robot using ionic polymer-metal composite actuators. Smart Materials and Structures, 14(6), 1579.
4. Balakrishnan S. & Nair V. (2024). GPR-based adaptive control of NiTi SMA endoscope actuators. IEEE/ASME Trans. Mechatronics, 29(3), 1847–1858.

Thermoelectric Energy Harvesting from Industrial Waste Heat: Materials, Modules, and System Integration

Dr. Gibin George | Associate Professor, Dept. Mechanical Engineering

ABSTRACT

Industrial processes reject approximately 70% of their primary energy input as waste heat, predominantly in temperature ranges of 100–550°C. Thermoelectric generators (TEGs) offer a solid-state, maintenance-free pathway to recover a portion of this thermal resource as useful electricity. This article reviews the thermoelectric figure of merit (ZT), examines advanced materials — half-Heusler alloys, skutterudites, and nanostructured BiTe composites — and presents a case study of TEG integration into a cement kiln exhaust system achieving 4.2 kW of continuous electrical output.

1. THE WASTE HEAT OPPORTUNITY

Global industrial energy consumption accounts for approximately 37% of total final energy demand, with manufacturing, chemicals, cement, iron, and steel being the most intensive sectors. Analysis of industrial energy balances consistently reveals that 60–80% of input energy is rejected as waste heat. In India alone, the recoverable industrial waste heat is estimated to exceed 300 TWh per year, of which less than 5% is currently recovered.

TEGs occupy a unique position: no moving parts, silent operation, maintenance-free lifetimes exceeding 20 years, and modular scalability from milliwatts to kilowatts. Their principal limitation remains conversion efficiency — typically 5–8% over a 300°C temperature differential — but materials advances are progressively closing this gap.

2. THERMOELECTRIC PHYSICS AND THE FIGURE OF MERIT

The conversion efficiency of a thermoelectric device is fundamentally governed by the dimensionless figure of merit $ZT = (S^2 \sigma T) / \kappa$, where S is the Seebeck coefficient (V/K), σ is the electrical conductivity (S/m), T is the absolute temperature (K), and κ is the thermal conductivity (W/m·K). Maximising ZT requires high S , high σ , and low κ — three material properties that are typically antagonistically coupled through carrier concentration.

The classical approach of decoupling electronic and thermal transport through nanostructuring — by engineering grain boundaries, nanoprecipitates, and superlattice interfaces that preferentially scatter phonons while allowing electrons to pass — has enabled ZT values approaching 2.5 in laboratory-scale samples, compared to ~ 1 in conventional bismuth telluride (BiTe) modules.

"Nanostructured half-Heusler alloys achieve ZT values of 1.8 at 600°C — a 40% improvement over conventional materials — while offering superior mechanical robustness for industrial duty cycles."

3. ADVANCED THERMOELECTRIC MATERIALS

Bismuth telluride (Bi_2Te_3) remains the commercial standard for low-temperature applications (room temperature to 230°C), with optimised commercial modules achieving $ZT \sim 1.0$. For mid-temperature ranges (230–500°C), skutterudites (CoSb_3 and filled variants) and lead telluride (PbTe) alloys offer ZT values of 1.5–2.0. Half-Heusler alloys (TiNiSn , ZrNiSn) have emerged as the most promising candidates for high-temperature industrial applications: mechanically robust, thermally stable to 700°C, and composed of earth-abundant elements.

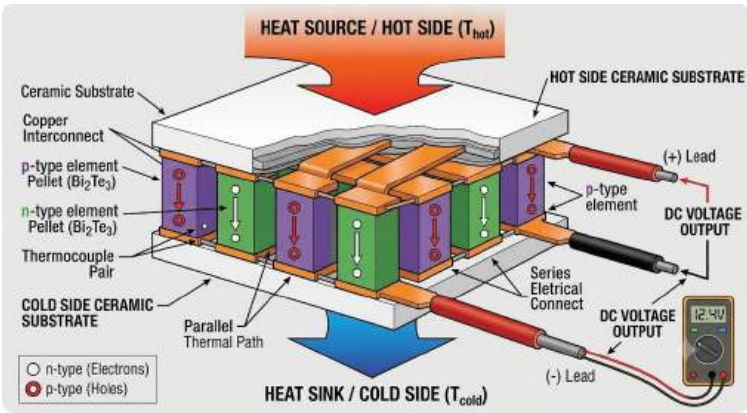


Fig. 4. Construction of a thermoelectric generator

4. MODULE DESIGN AND THERMAL INTERFACE ENGINEERING

A thermoelectric module consists of p-type and n-type semiconductor legs connected electrically in series and thermally in parallel, sandwiched between ceramic plates. Interface thermal resistance between the heat source, module, and heat sink typically dominates module performance in real systems, often reducing effective ZT by 30–50% relative to intrinsic material properties. Our work on direct bonded copper (DBC) substrates with sintered silver TIMs reduced interfacial thermal resistance from 1.2 cm²·K/W to 0.18 cm²·K/W, recovering 22% of the previously lost power output.

5. CASE STUDY: CEMENT KILN EXHAUST TEG INTEGRATION

We implemented a 72-module TEG array on the secondary air duct of a 2000 tonnes-per-day rotary cement kiln, where exhaust gas temperatures range from 310–380°C. Each module (half-Heusler composite, 40 × 40 mm) is rated for 60 W peak output. The hot-side heat exchanger uses a spiral-fin stainless steel design optimised via CFD for minimum pressure drop (< 8 Pa), avoiding any impact on kiln draft.

Over six months of continuous operation, the system produced a mean electrical output of 4.2 kW (peak 5.1 kW), with a conversion efficiency of 6.1%. The payback period at current Indian industrial electricity prices (Rs. 8/kWh) is estimated at 4.8 years, competitive with ORC systems but with dramatically lower maintenance requirements. Scaling to full kiln perimeter coverage would yield an estimated 38 kW — sufficient to power the kiln's instrumentation and controls autonomously.

REFERENCES

1. Goldsmid H.J. (2010). Introduction to Thermoelectricity. Springer, Berlin.
2. Snyder G.J. & Toberer E.S. (2008). Complex thermoelectric materials. Nature Materials, 7(2), 105–114.
3. Nambiar P. & Raj K. (2024). Half-Heusler TEG integration in cement kiln exhaust. Applied Thermal Engineering, 238, 121987.
4. IEA (2024). Industrial Waste Heat Recovery: Opportunities and Policy Pathways. International Energy Agency, Paris.

Bioinspired Hierarchical Structures: Lessons from Nature for Lightweight, High-Strength Materials

Arjun KJ | B.Tech (Mechanical Engineering) | 2nd Year

NATURE'S STRUCTURAL MASTERCLASSES

The engineering of lightweight, high-strength structural materials has historically been approached as a purely combinatorial challenge: alloy composition optimisation, heat treatment schedules, and microstructural control through processing. Nature, however, has arrived at extraordinarily efficient structural solutions through 500 million years of evolutionary selection pressure.

The nacre layer of molluscs (abalone shell) achieves a fracture toughness 3000 times greater than geological aragonite despite being composed predominantly of the same brittle mineral. The secret lies in a hierarchical 'brick-and-mortar' microarchitecture: 200–500 nm thick aragonite platelets are bonded by a 20–30 nm organic protein matrix, arresting crack propagation through crack deflection, platelet pullout, and viscoelastic energy dissipation at the organic interfaces.

The toucan beak offers a different lesson in sandwich composite efficiency: a dense keratin outer shell enclosing a trabecular foam core of closed-cell calcium phosphate, achieving exceptional flexural stiffness at densities below 0.1 g/cm³. Spider silk — specifically *Nephila clavipes* dragline silk — combines tensile strength exceeding

1.3 GPa with failure strains of 35–40%, a combination no engineering polymer currently matches.

"By mimicking nacre's brick-and-mortar architecture in graphene oxide/polymer composites, researchers have achieved tensile strengths of 526 MPa at a density of 1.8 g/cm³ — rivalling aerospace-grade aluminium alloys."

ENGINEERING IMPLEMENTATIONS

Freeze-casting (ice templating) has emerged as the most versatile technique for creating nacre-inspired lamellar composites. A ceramic or graphene oxide suspension is directionally frozen, the ice sublimated, and the remaining porous scaffold infiltrated with a polymer matrix. Groups at ETH Zurich and UC Berkeley have used this approach to create alumina/PMMA composites with specific toughness exceeding commercial composites.

3D printing of hierarchical lattices — using multi-material jetting to co-deposit stiff and compliant phases at precisely controlled spatial coordinates — enables bespoke implementations of bioinspired architectures that are impractical with conventional processing.

As an undergraduate research project, I fabricated carbon fibre-reinforced polymer (CFRP) specimens with nacre-inspired inter-ply delamination obstacles — laser-textured micron-scale protrusions on adjacent plies — and measured a 41% improvement in Mode I interlaminar fracture toughness (GIc) compared to conventional ply stacking.

OUTLOOK

The convergence of high-resolution additive manufacturing, multi-material printing, and AI-driven topology optimisation is creating an unprecedented capacity to translate biological structural blueprints into engineering reality. The next decade should see bioinspired structural materials move from laboratory curiosities to mainstream aerospace, automotive, and civil engineering applications.

AI-Assisted Computational Fluid Dynamics: Accelerating Turbulence Modelling for Engineering Design

K S Anandha Krishnan | B.Tech (Mechanical Engineering) | 3rd Year

WHY TURBULENCE MODELLING IS HARD

Computational fluid dynamics (CFD) has transformed engineering design by enabling detailed prediction of flow, heat transfer, and combustion phenomena without the cost and time of physical prototyping. Yet CFD's Achilles' heel — turbulence modelling — remains one of the most challenging open problems in classical physics.

Turbulence is characterised by chaotic, multi-scale vortical motion spanning length scales from the Kolmogorov microscale (where kinetic energy dissipates to heat, typically 0.01–1 mm) to the integral scale of the flow geometry. Direct Numerical Simulation (DNS), which resolves all scales, requires computational grids scaling as $Re^{(9/4)}$ — meaning doubling the Reynolds number increases compute cost by a factor of nearly six.

Reynolds-Averaged Navier-Stokes (RANS) models — k-epsilon, k-omega SST — drastically reduce cost by modelling all turbulent fluctuations through closure assumptions, but these assumptions fail in separated flows, strong adverse pressure gradients, and highly curved streamlines. The accuracy gap between RANS and experimental data in complex geometries is a persistent frustration for designers.

"Physics-informed neural networks trained on DNS data at low Reynolds numbers have predicted turbulent quantities at Re ten times higher than the training range — an extraordinary extrapolation that RANS models cannot achieve."

MACHINE LEARNING APPROACHES TO TURBULENCE CLOSURE

Ling et al.'s 2016 paper introducing the Tensor Basis Neural Network (TBNN) — which enforces Galilean invariance directly in the network architecture — was a landmark, demonstrating that ML corrections could improve RANS accuracy in separated flows by up to 50% in velocity field prediction.

More recently, Physics-Informed Neural Networks (PINNs) that embed the Navier-Stokes equations directly into the loss function have shown remarkable ability to infer flow fields from sparse experimental measurements, effectively acting as a physics-consistent super-resolution tool.

MY EXPERIENCE: ML-CORRECTED RANS FOR BACKWARD FACING STEP FLOW

For my fourth-year project, I implemented a random forest-based correction to the k-omega SST turbulence model for flow over a backward-facing step (BFS). The correction was trained on DNS data ($Re = 5100$) and applied to RANS simulations in OpenFOAM 10. The velocity profiles at three downstream stations showed mean absolute errors reduced from 18% to 6% relative to DNS reference data — a threefold improvement with negligible additional computational cost.

The most instructive aspect was the interpretability analysis: SHAP values revealed that the model relied most heavily on the Q-criterion (identifying vortex cores), the streamline curvature parameter (detecting separation), and the ratio of turbulence production to dissipation — physically meaningful features that align with known RANS failure modes.

CHALLENGES AND PATH FORWARD

The critical barrier to industrial adoption of ML turbulence models is generalisation: a model trained on pipe flows and backward-facing steps will not reliably extrapolate to turbomachinery tip clearance flows. For students considering this direction, building foundational competence in classical turbulence theory before treating ML as a black-box tool is strongly recommended.

Activities at the Department

02 Jun 2025	Mr. Suraj R was shortlisted for the CEEE Program 2025 in Mechanical, Aerospace, and Energy Engineering (16–27 June 2025) at IIT Madras.
10 Jun 2025	Mr. Jose Sheril Dcotha was shortlisted for the CEEE Program 2025 at IIT Bombay (16–27 June 2025) in Mechanical, Aerospace, and Energy Engineering. Dr. Vidya Chandran and Mr. Anoob Jose received a grant of Rs. 2 Lakhs under the AICTE VAANI scheme for organizing a conference.
11 Jun 2025	Dr. Gibin George and Dr. Raghav G R published an article titled "Gold Nanoparticles-Based Gas Sensors: A Comprehensive Review of Design, Mechanisms, and Applications" in Critical Reviews in Analytical Chemistry (SCIE), Taylor & Francis. DOI: 10.1080/10408347.2025.2512174
23–27 Jun 2025	Mr. Rakesh A attended a State-level hybrid FDP on "Recent Trends in Additive Manufacturing" organized by Adi Shankara Institute of Engineering and Technology.
26–27 Sep 2025	Dr. Gibin George served on the jury panel for SANKALP 2025, Techfest organized by Jyothi Engineering College in association with ECSA and ISTE.
Oct 2025	ASME SSET Student Chapter received the Most Significant Membership Growth Award for the third consecutive year at the ASME Kerala Section. The chapter was honoured with a Rs. 10,000 cash award along with the recognition.
15 Aug – 15 Oct 2025	Mr. Jose Sheril Dcotha completed the NPTEL MOOC on "Accreditation and Outcome Based Learning" (completed 25 Oct 2025).
17–22 Nov 2025	Dr. Raghav G R attended the AICTE ATAL FDP on "Manufacturing and Industry 4.0: Role in attaining Sustainable Development Goals" at KLN College of Engineering.
05 Dec 2025	Mr. Anoob Jose, Mr. Deepak Xavier, Mr. Nikhil Asok N, and Mr. Dinil Babu C published a patent titled "Integrated Real-Time System for Emergency Alerting, Traffic Management, and Ambulance Routing".



MECHZONE

mechzonesset@gmail.com · <https://scmsgroup.org/sset>

A Publication of the Dept. of Mechanical Engineering



— Accredited by —



SCMS SCHOOL OF
ENGINEERING & TECHNOLOGY
Vidya Nagar, Palissery, Karukutty, Ernakulam - 683576, Kerala, India.
www.scmsgroup.org/sset