POWER TALK– TURBINES

Turbine innovators leading low-carbon revolution

Digitalisation and advanced materials innovations such as digital twins, predictive maintenance and high-efficiency designs enhance turbine performance, reliability and sustainability.

Turbines play a major role in the transition to low-carbon energy. Digitalisation and advanced materials innovations such as digital twins, predictive maintenance and high-efficiency designs are enhancing turbine performance, reliability and sustainability. S Narayana Prasad says these collectively support cleaner energy generation and smarter asset management in increasingly demanding operating environments. Let us hear from him in detail about the innovations and strategies being used in the industry.

How are digital twins and predictive maintenance technologies integrated into modern turbine systems?
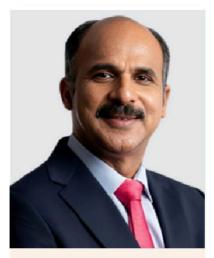
In the power sector, digital twins and predictive maintenance technologies are increasingly integrated into modern turbine systems to enhance performance, reliability and efficiency.

Digital twins are being utilised to create real-time virtual replicas of physical turbines, enabling operators to simulate and monitor turbine behaviour under various operational conditions. This digital model supports continuous performance analysis, helping to identify inefficiencies or deviations from optimal operation. It also facilitates remote diagnostics, which reduces downtime and maintenance costs. Additionally, digital twins allow operators to simulate different maintenance strategies or design modifications before implementation, enhancing decision-making and operational efficiency.

Predictive maintenance leverages sensor data to monitor key parameters such as temperature, vibration, pressure, and rotational

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speed. This data is analysed using machine learning algorithms that assess historical and real-time information to predict potential failures or component degradation. These insights enable more accurate maintenance scheduling, allowing for planned interventions that prevent unexpected breakdowns and extend the lifespan of equipment. As a result, unplanned outages are minimised, leading to significant cost savings and improved plant availability. Overall, integrating digital twins and predictive maintenance in turbine systems enables smarter, more proactive asset management, enhancing reliability, reducing operational costs and supporting cleaner energy generation in the power sector.

What role do turbines play in transitioning to low-carbon energy, and how have recent innovations supported this shift?

Decarbonisation strategies increasingly incorporate innovative technologies such as heat pumps, energy storage, MVR (Mechanical Vapor Recompression) and ORC (Organic Rankine Cycle) systems to reduce

greenhouse gas emissions and enhance energy efficiency.

Advancements in energy technologies play a pivotal role in accelerating decarbonisation across sectors. Larger and more efficient steam turbines, driven by blade design, materials, and aerodynamics innovations, have significantly increased electricity generation capacity while reducing the carbon footprint per output unit. Heat pumps contribute by replacing fossil fuel-based heating and cooling systems; by transferring heat from the environment (air, ground, or water), they offer a cleaner alternative, particularly when powered by renewable electricity.

Energy storage technologies, including batteries and thermal storage, enhance grid reliability and flexibility by balancing supply and demand. This enables greater integration of intermittent renewable sources and reduces dependence on fossil-fuel-based peaking plants.

In industrial processes, Mechanical Vapor Recompression (MVR) improves energy efficiency by capturing and reusing waste heat in applications like evaporation and desalination, thus minimising the need for additional fossil fuel input. Similarly, the organic rankine cycle (ORC) system converts low-grade waste heat into clean electricity using organic fluids, enabling the productive use of otherwise wasted thermal energy.

Collectively, the integration of efficient turbines, heat pumps, energy storage, MVR, and ORC systems forms a comprehensive strategy for decarbonisation, thereby boosting energy efficiency, increasing renewable energy adoption, harnessing waste heat and ultimately reducing fossil fuel reliance to pave the way for a sustainable low-carbon future.

How are manufacturers addressing the challenges of turbine durability

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and performance in extreme operating environments?

Manufacturers are using high-performance materials that conform to industry standards (e.g., ASTM, ASME, NACE) to ensure steam turbine components maintain mechanical integrity under extreme conditions, such as high temperature, pressure, and corrosive media.

Advancements in steam turbine technology have significantly improved performance, reliability and adaptability to modern energy demands. High-temperature alloys such as advanced nickel-based superalloys and improved stainless steels are now widely used in components like blades and rotors. These materials retain strength and resist creep even under extreme temperatures, ensuring long-term durability. Complementing these are protective coatings such as WcCr Cr, MCrAlY and ceramic thermal barrier coatings shield turbine blades from erosion, corrosion and high-velocity steam particles. Surface treatments, including shot peening, nitriding and laser processes, further enhance fatigue resistance and extend component lifespan.

Improved blade design and aerodynamics are also at the forefront of turbine innovation. Techniques like 3D blade profiling reduce aerodynamic losses and stress concentrations, boosting efficiency. Particular attention is given to last-stage blades (LSBs), which face high erosion and flutter risks. Modern LSBs often feature snubber-less or integrally shrouded designs that minimise vibrational stresses. Computational Fluid Dynamics (CFD) simulations play a crucial role in optimising blade geometries across varied operating conditions and improving robustness and performance.

To manage heat effectively, turbines incorporate internal cooling pathways in the inlet, exhaust and casing regions to lower thermal stresses. Thermal barrier coatings further minimise the heat load on vital components, enhancing reliability. Modular and flexible designs have also emerged, enabling easy upgrades, repairs and customisation for different applications such as combined-cycle or geothermal setups.

Moreover, turbines are increasingly designed for load-following capability, allowing them to endure frequent cycling without premature fatigue. Digitalisation has transformed turbine monitoring and maintenance. Condition monitoring systems (CMS) provide real-time insights into temperature, vibration and pressure, enabling early fault detection. Predictive maintenance powered by AI and machine learning identifies wear trends and prevents unexpected failures. Digital twins simulate operational behaviour, supporting performance optimisation and efficient maintenance planning.

Sealing and bearing technologies have also advanced. Optimised labyrinth and brush seals reduce steam leakage and withstand high temperatures, while hydrodynamic and magnetic bearings improve reliability under transient and high-load conditions. Additive manufacturing, especially 3D printing, has revolutionised component design and repair, facilitating complex geometries and superior material properties.

Environmental adaptations are crucial. Turbines in geothermal or solar applications are engineered to cope with high moisture or thermal variability. New designs account for carbon capture integration, ensuring compatibility with steam purity and backpressure changes associated with Carbon Capture and Storage (CCS) systems. These innovations collectively elevate steam turbine efficiency, resilience and environmental compatibility.

What are the key maintenance strategies adopted recently for turbines to enhance efficiency while minimising unplanned downtimes?

Recent maintenance strategies for steam turbines have increasingly focused on predictive, digital and condition-based approaches to improve efficiency and availability and reduce unplanned downtimes. Operators and OEMs adopt certain key maintenance strategies. Predictive maintenance uses AI and machine learning to analyse real-time data such as vibration, temperature, pressure and acoustic signals for early anomaly detection. By recognising patterns in historical data, AI models can forecast failures like bearing wear or blade fatigue. Condition-based maintenance (CBM) relies on the actual health of components rather than fixed schedules. It employs techniques such as vibration analysis (ISO 10816/7919), oil analysis (viscosity, TAN, water content, metal particles), thermography and rotor dynamics monitoring to ensure timely and efficient maintenance based on equipment condition. This approach helps extend service intervals without compromising safety or performance.

Turbine maintenance and monitoring have evolved significantly by integrating advanced digital technologies. Remote Monitoring and Diagnostics (RMD) enable 24/7 surveillance of turbines via SCADA or DCS systems, providing real-time alerts on performance drift, abnormal vibrations or thermal stress. This facilitates faster, expert-driven decisions to mitigate potential failures. Digital Twin technology further enhances operational intelligence by creating virtual models of turbines using real-time sensor data and historical records. These replicas allow the simulation of various conditions, optimising maintenance schedules, predicting component degradation, and assessing load impacts.

Inspection practices have also improved with Advanced Non-Destructive Examination (NDE) techniques such as phased array ultrasonic testing (PAUT), eddy current testing (ECT) and laser shearography for blade inspection. These methods offer precise detection of cracks, erosion and material loss during outages or condition-based inspections. In the event of a failure, Root Cause Failure Analysis (RCFA) tools like FMEA, RCA and 8D are employed to uncover underlying issues.

Additionally, operator training has been revolutionised through Augmented Reality (AR) and Virtual Reality (VR), which provide immersive, hands-on experiences and real-time guidance, enhancing safety and efficiency during turbine operations.