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Advanced Turbine Research for Sustainable Propulsion and Power

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The global imperative to transition towards sustainable energy solutions has driven significant advancements in turbine technology, particularly in propulsion and power generation. The Purdue Experimental Turbine Aerothermal Laboratory (PETAL) is at the forefront of these developments, investigating new approaches to fluid machinery in novel thermal cycles that push the boundaries of traditional applications using advanced diagnostics [1]. This keynote will provide a comprehensive overview of recent research conducted at PETAL, conducting research that spans a range of technology readiness levels (TRLs), from foundational studies to application-focused advancements. Each application presents unique challenges, requiring integrating theoretical, computational, and experimental methods.

Among the promising technologies for high-efficiency power generation, **supercritical CO_2** (sCO_2) cycles have garnered considerable interest for their compactness, operating in closed Brayton cycles. PETAL's research into sCO_2 cycles focuses on optimizing turbine blade, rotor tip, and stator hub disk leakage and rim-seal geometries that maximize efficiency while managing heat loads in high-pressure environments. A high-pressure turbine blade has been designed for a 350 MWe Oxifuel power cycle using a surrogate-assisted genetic algorithm, with the dual objectives of improving efficiency and reducing blade heat load. The optimization generated approximately 3,000 three-dimensional Reynolds-Averaged Navier-Stokes simulations. The resulting optimal blades were experimentally investigated in PETAL's annular rig, where sCO_2-optimized geometries were evaluated at relevant Reynolds numbers [2]. **Ammonia** is emerging as an alternative aviation fuel due to its higher density and boiling point compared to hydrogen, which reduces the need for extensive retrofitting of current aircraft architecture. The possibility of retrofitting existing engines for ammonia-based cycles offers a sustainable path for aviation without a complete overhaul of existing fleet infrastructure. At PETAL, research focuses on optimizing the engine cycle, designing and testing the heat exchangers, and assessing different turbine concepts. In order to retrofit aircraft engines for ammonia fuel, the open-source Toolbox for Modeling and Analysis of Thermodynamic Systems was adapted to simulate ammonia-fueled engines with the integration of heat exchangers and other advanced technologies. The analysis revealed that using ammonia as a heat sink for intercooling and recuperation significantly improves cycle efficiency, reducing fuel consumption by 3%-9% over the baseline engine. Further optimization of heat exchanger geometry minimizes their size and fuel consumption at cruise, while the Waste Heat Recovery cycle supplies the aircraft's 250 horsepower electrical power demand. [3]

Hydrogen-based rotating detonation combustion (RDC) offers a significant efficiency boost by using detonation waves in a short combustor, maximizing energy release [4]. However, integrating RDCs with turbines presents challenges due to the pulsating high-speed exhaust flows, which impose unsteady loads on turbine components. PETAL's research focuses on creating turbine designs that effectively manage these intense conditions, maintaining efficiency and operational durability. PETAL research provides a deeper understanding of the aerothermal behavior of turbines in unsteady flow fields, helping to shape design guidelines for turbines compatible with RDCs. PETAL developed various turbine configurations—supersonic axial [5], highly diffusive turbine vanes [6], radial [7], mixed-flow, and bladeless [8] —each tailored for unique flow dynamics. PETAL's analysis highlights that optimized blade geometries and configurations can significantly reduce losses, enhancing efficiency for sustainable applications.

Efficient turbine operation requires **minimizing aerodynamic losses** commonly arising from flow separation, shock-wave interactions, and secondary flow effects. This section will address the fundamental flow mechanisms associated with turbine loss generation, essential to assess turbine efficiency [9]. PETAL has focused on two mechanisms: boundary layer separation and the unstarting process in supersonic flows. First, we investigated the establishment of the boundary layer under transient operation [10] and the reattachment of a separated boundary layer using flow control strategies [11]. Anchored in these findings in collaboration with AFRL, we are investigating a new low-pressure turbine geometry [12]. Regarding the starting process, we have developed tools [13] suitable for optimizing supersonic turbine passages to enable startability under steady and transient inlet conditions.

As clean aviation technology progresses, reducing development timelines is essential for swift market entry and extended climate benefits. Therefore, concurrent with our fundamental studies, PETAL's novel gas turbine research facility, based on an M250-C40B turboshaft engine, offers a pathway for **accelerated high TRL validation** of novel turbine technologies for clean thermal cycles [14]. The M250-C40B-based facility is particularly suited to studying alternative fuel integration and combustor-turbine interactions. Configured with a partial turbo-electric setup, the facility supports exploring hybrid propulsion architectures. PETAL has developed diagnostic tools for high-resolution aerothermal analysis to support advanced turbine research. These diagnostic advancements enable PETAL to capture intricate details of turbine flow dynamics, allowing precise validation of computational models and optimization of turbine designs. **Future directions** include continued exploration of alternative turbine architectures, investigating the loss mechanisms at a much more fundamental level, uncovering the root cause of flow separation, and diagnostic precision. This keynote aims to inspire innovation in clean propulsion.

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