Popular science summary

Since the dawn of the Jet Age, humanity has relied on the gas turbine engine, which operates on a traditional, subsonic combustion principle known as "deflagration". Despite being engineering marvels, these engines are approaching a developmental plateau because they are fundamentally limited by the thermodynamics of their cycle. Consequently, squeezing out even a single percentage point of extra efficiency now requires astronomical investment. With the aviation and electricity sectors each responsible for a significant portion of global warming contributions, there is urgent pressure to drastically reduce fuel consumption. To meet global power demands sustainably, a paradigm shift is required. This thesis explores a highly promising candidate: the Rotating Detonation Combustor (RDC). Unlike conventional engines that burn fuel relatively slowly and lose pressure, an RDC utilises continuous, controlled detonations that travel faster than the speed of sound. This process compresses the fuel mixture, offering a distinct advantage known as pressure gain, which could theoretically boost engine efficiency by tens of percentage points. In a typical RDC, a detonation wave races around an annular gap between two nested cylinders at speeds exceeding 1,000 metres per second, consuming fresh reactants and leaving pressurised exhaust gas to produce thrust or spin a turbine.

While the concept is simple, the interior of an RDC is a chaotic and harsh environment where experimental sensors often fail to capture the sub-microsecond events occurring. This creates a "black box" problem where researchers struggle to understand engine instabilities and inefficiencies, preventing the design of reliable engines. To solve this, the research utilises high-fidelity Computational Fluid Dynamics, specifically Large Eddy Simulation, which acts as a "numerical microscope" powered by supercomputers. By dividing the combustor into millions of tiny cells, researchers can freeze time to see exactly what is happening inside the three-dimensional chamber. The research applied this method to replicate two real-world engines from the US Air Force Research Laboratory (AFRL) and the University of Cincinnati. Simulations of the AFRL design revealed that the detonation wave acts like a fast-acting valve, momentarily blocking fuel injection and creating a fresh air "refill zone" that dictates how the next wave will burn. The study also highlighted critical weaknesses, such as "parasitic" burning where fuel burns slowly (like a conventional flame) before the wave arrives, thereby wasting the pressure and efficiency gain potential.

A broader question emerged regarding the number of detonation waves spinning within the combustors, as predicted by the simulations. Under standard conditions, the computational results perfectly matched laboratory observations, predicting a single, stable revolving wave for both the AFRL and Cincinnati designs. However, when the virtual engines were pushed harder, such as doubling the mass flow or enriching the air with oxygen, the models predicted an additional co-rotating wave compared to both experiments. Extensive sensitivity studies could not eliminate this extra wave, leading to the hypothesis that the simulation may be missing the dynamic ‘breath’ of a real engine. In reality, the combustors are connected to reactant supply reservoirs (known as plenums) that act like a dynamic buffer pool of fluid, whereas the computational model treated the reactant supplies as direct streams of inflow. Simplifying this inflow condition might have artificially stabilised the virtual combustor, allowing an extra detonation wave to survive. Further research is needed to couple these supply systems into the simulations to test this deduction. Ultimately, by validating these high-fidelity models and identifying where they succeed and struggle, this thesis aims to move the field from simple observation to predictive design, empowering engineers to confidently develop the next generation of sustainable and high-performance aero-engines.