Mixed Mode Propulsion for Reusable Aerospace Launchers

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Overview

There is currently no aircraft engine which can take off and reach hypersonic speeds (Mach 5 and above) unassisted by another engine or rocket. Turbojets are well-established engines capable of supersonic flight (up to Mach 3) while ramjet engines exclusively fly at supersonic and hypersonic speeds; however, neither engine bridges the gap. This project modelled the RB545 engine to determine which engine parameters affected the performance, measured by the thrust to weight ratio.

Applications:

- Further hypersonic research
- Military uses, surveillance and ordnance delivery
- Reusable space launchers

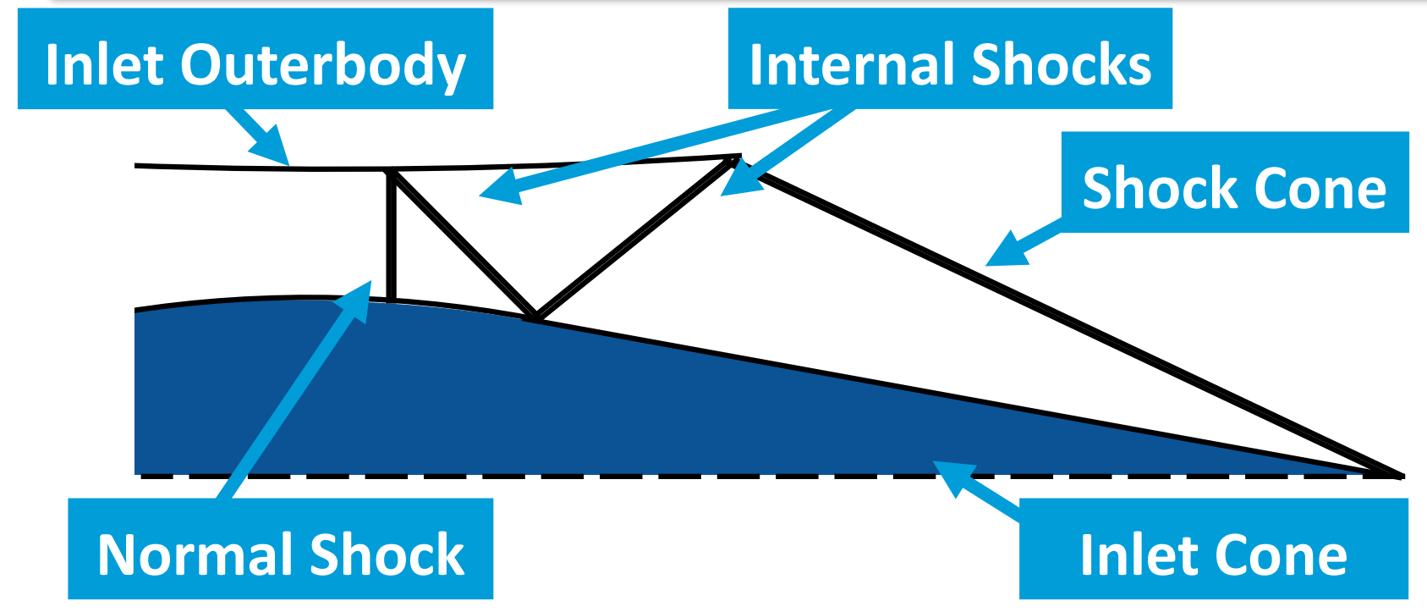
Project Aims:

- Model precooled turbo-ramjet engine in MATLAB and C++
- Perform parametric study of cycle parameters such as pressure ratios and inlet temperatures to investigate effect on engine performance

Method

Supersonic Intake:

- Shock waves form in the shape of a cone at the intake of supersonic aircraft.
- To recreate this and find the conditions at the inlet of the engine, a model was coded to find the flow profile across the shock cone for given inlet conditions.
- The ram compression from the internal shocks were then modelled using the method of characteristic and the isentropic relations for flow properties across shock waves.
- Method of characteristics was continued until a normal shock was found, at which point the flow properties were calculated.
- The flow is supersonic before the normal shock and subsonic after.



Oblique Shocks:

- As the shock angle increased, the reduction in velocity from the free-stream to the cone angle became larger.
- Across shocks, the normal component of velocity is reduced while the tangential is unchanged; so to change the angle of the flow to be parallel to the cone, a greater reduction in the normal component is required.
- Hence, the after-shock velocities decreased as the shock angle increased, even for constant free-stream Mach numbers.

Engine Model:

- Each component of the engine was modelled: Intake, Precooler, Air Compressor, Liquid Hydrogen Pump, Combustion Chamber, Hydrogen Turbine, Nozzle.
- Enthalpy balances across each component allowed the properties of the air to be calculated at each stage.
- Detailed blade-to-blade analyses of the turbomachinery (pump, compressor and turbine) were performed in order to calculate machine diameters.
- After sizing the machines, their weights could be found to estimate the weight of the whole engine.

Blockage:

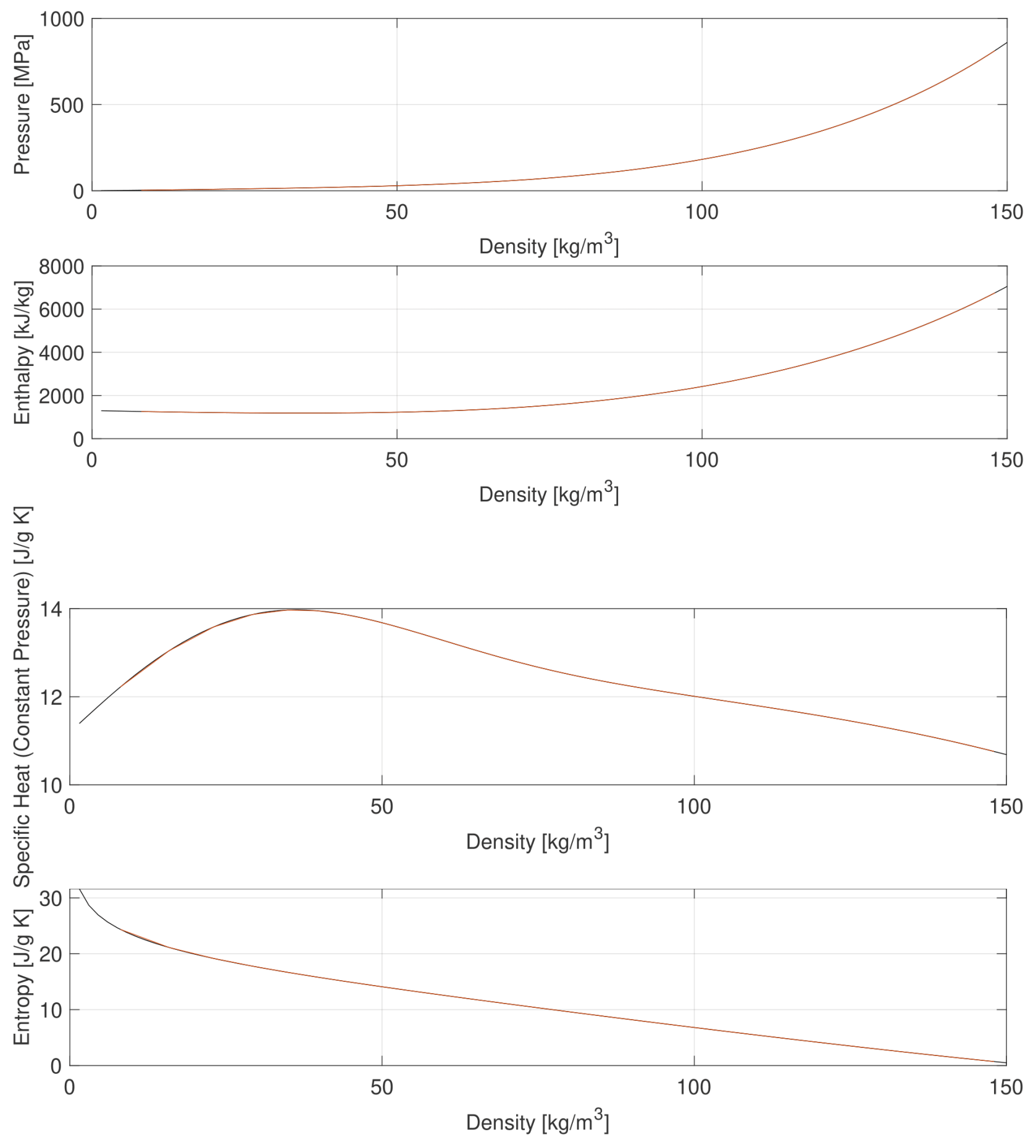
- A boundary layer forms on the surfaces inside turbomachinery; flow velocities are reduced in this layer as viscous forces become comparable to the inertial forces.
- Due to the reduced velocity, the effective fluid area is also reduced and so to maintain continuity, larger diameter machines are needed.

Blade Diffusion - Compressor and Pump:

- The fluid pressure increases across compressor stages; thus, the flow encounters an increasing pressure gradient as it passes over blades.
- This causes boundary layer growth on the surface, which can lead to separation of the flow.
- To prevent this, empirical correlations were used to set the blades exit angles of the stator.

Hydrogen Properties:

- The state of hydrogen was needed at each point in the cycle to accurately model each process.
- A function was written to take the density and temperature of a state and return properties such as pressure, enthalpy, entropy and specific heat.
- These were all calculated from the derivatives of an empirical equation for the Helmholtz free energy.
- The results for each property were compared against the NIST Chemistry WebBook [1] and found to be highly accurate, with the largest percentage error was found to be 0.0286%.
- Isothermal plots at 100 K of the comparisons are shown below, with the function data in black and the NIST data overlayed in red.



Isothermal Plots Comparing NIST [1] (red) and Function Data (black) for Pressure, Enthalpy, Specific Heat and Entropy

Acknowledgements:

Dr Luca Di Mare

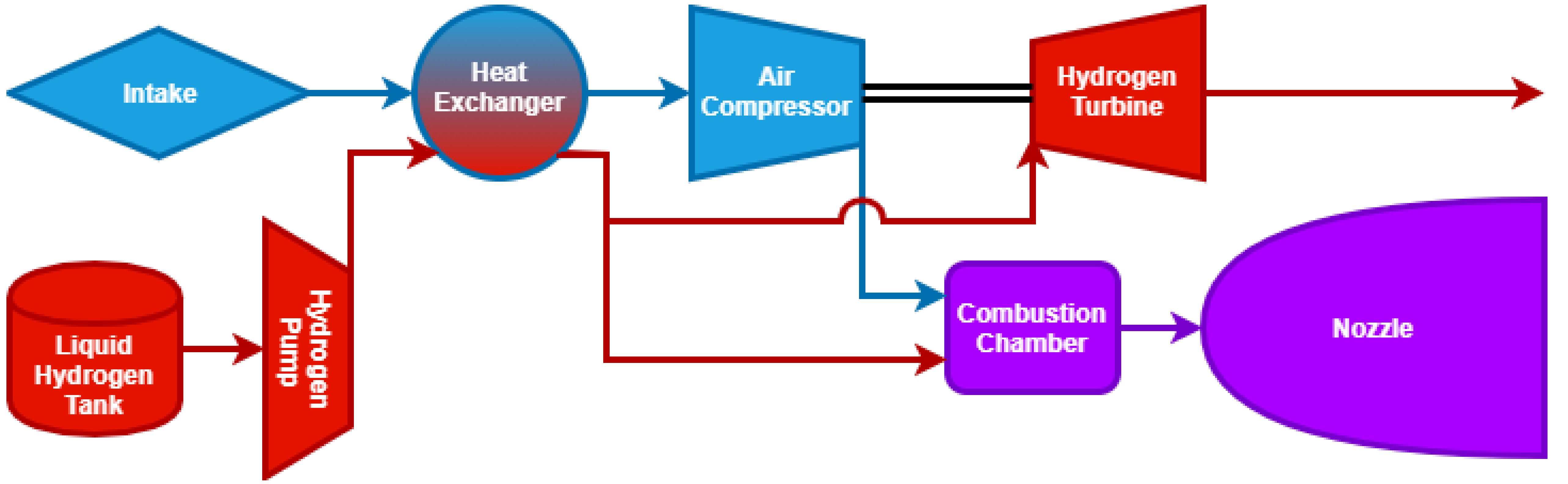
References:

[1] "Thermophysical Properties of Fluid Systems" in NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, https://doi.org/10.18434/T4D303

Background

RB545 Engine:

- The RB545 was developed by Rolls-Royce in the 1980's and was the first precooled air-breathing rocket engine. It was the predecessor to the SABRE, currently being designed by Reaction Engines, an aerospace manufacturer based in Oxfordshire.
- It used both ram- and mechanical-compression. Ram-compression uses the forward momentum of the aircraft to force and compress air into the intake; thus, turbo-ramjets make use of both compression methods.
- After the ram-compression, the air was cryogenically cooled by liquid hydrogen in the heat exchanger. This allowed the air compressor to operate with higher fluid velocities while also being lighter as heavier heat resistant alloys were not needed.
- The hydrogen and air flow would mix and ignite in the combustion chamber, as with typical turbojets, before exhausting through the nozzle where the thrust was produced.
- A separate stream of hydrogen would be passed to a turbine whose generated power would run the compressor and pump.
- This cycle is illustrated below:



Thermodynamic Cycle of the RB545 Engine

Air (Blue), Hydrogen (Red), Combustion Gases (Purple)

Conclusion

Review:

This project successfully modelled the components in a turbo-ramjet engine, based on the RB545. The supersonic intake produced an accurate shock cone profile, calculated the cone angle and inlet conditions to the engines by numerically integrating the Taylor-Maccoll equation. The hydrogen properties function also precisely determined the required states of hydrogen throughout the machine from the Helmholtz free energy. Estimates could be made for the engine weight from these three sections to lay the groundwork for a parametric study to be conducted in the next stage of this research.

Applications:

The work achieved in this project has set the foundation for improving performance in turbo-ramjets, aiding the future of mixed-mode propulsion research.

Future Work:

SABRE Model - A natural progression to this project would involve modelling the SABRE. The model would be very relevant to Reaction Engines as the SABRE engine is currently in development. The primary difference between the two engines is the incorporation of another fluid cycle of helium, which transfers heat from the inlet airflow to the combustion gases and hydrogen flow, allowing for the operation of a helium turbine used to power other turbomachinery. An investigation into different working fluids other than helium would provide an insight into the advantages and disadvantages of different modelled fluids.

Losses - In order to simplify calculations, a number of losses were not considered in the model. Viscous losses in the ducts and pipes connecting components, and tip leakage and profile losses in the turbomachinery could all be incorporated in order to provide more accurate exit flow conditions to produce better thrust calculations for performance evaluation.

Turbomachinery - A possible extension to the project involves modelling the pump in a centrifugal configuration. Lower fluid velocities were possible for the liquid hydrogen and an axial flow pump may not have been best suited to the flow conditions. Additionally, novel research into the correlations used to reduce blade diffusion would allow for more freedom in setting blade exit angle and characteristics.