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Theoretical Analysis of a Combined-Cycle (Turbojet + Ramjet) Propulsion System

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Abstract: This paper investigates the theoretical performance of a combined-cycle propulsion system integrating turbojet and ramjet engines. Turbojets operate effectively in subsonic and transonic regimes, while ramjets excel in supersonic conditions but require high inlet speeds to function. A hybrid engine allows a supersonic vehice to operate efficiently across a wide Mach range. Using thrust equations, Brayton cycle efficiency, and Rayleigh flow theory, this paper models the performance of both engine types and identifies transition conditions for optimal operation.

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I. INTRODUCTION

Modern missile propulsion systems face limitations when operating across a wide speed range. Turbojet engines are suitable for subsonic and transonic flight (up to ~Mach 2–2.5) but suffer from high drag and low efficiency at higher Mach numbers. Ramjets, in contrast, thrive at supersonic speeds (Mach 2–5) but cannot start from zero velocity due to their lack of mechanical compressors.

To achieve sustained supersonic flight, advanced missile designs (e.g., Kh-31 and SR-72 concepts) are exploring combined-cycle propulsion systems, where a turbojet accelerates the missile to a sufficient Mach number, after which a ramjet takes over. This paper presents a theoretical analysis of such a hybrid propulsion system.

II. BASIC WORKING OF TURBOJET AND RAMJET ENGINES

➢ *Turbojet Engines:*

The gas turbine has an air inlet which includes inlet guide vanes, a compressor, a combustion chamber, and a turbine (that drives the compressor). The compressed air from the compressor is heated by burning fuel in the combustion chamber and then allowed to expand through the turbine. The turbine exhaust is then expanded in the propelling nozzle, where it is accelerated to high speed to provide thrust. [1]

➢ *Ramjet Engines:*

The first part of a ramjet is its diffuser (compressor) in which the forward motion of the ramjet is used to raise the pressure of its working fluid (air) as required for combustion. Air is compressed, heated by combustion and expanded in a thermodynamic cycle known as the Brayton cycle (explained later on in detail), before being passed through a nozzle to accelerate it to supersonic speeds and generate forward thrust.

Ramjets are much less complex than turbojets or turbofans, requiring only an air intake, a combustor, and a nozzle to be built. Additionally, ramjets have little to no moving parts - liquid-fuel ramjets have only a fuel pump, whilst solid-fuel ramjets lack even this. A detailed schematic is provided later on, exemplifying this statement. [2]

Estimates made in 1964 for the Concorde design-which used turbojet engines-at Mach 2.2 showed the penalty in range for the supersonic airliner, in terms of miles per gallon, compared to subsonic airliners at Mach 0.85 (Boeing 707, DC-8) was relatively small. This is because the large increase in drag is largely compensated by an increase in powerplant efficiency (the engine efficiency is increased by the ram pressure rise, which adds to the compressor pressure rise, the higher aircraft speed approaches the exhaust jet speed, increasing propulsive efficiency) [3]. Ramjets, on the other hand, require an air intake velocity of at least Mach 1 or greater, depending on the type of engine [4]. Normally, the vehicle that hosts the ramjet is accelerated to Mach 1 by means of a secondary propulsion system, such as a turbofan or a turbojet engine itself. A more unconventional method is to accelerate it past Mach 1 using solid rocket propellant.

➢ *Drawbacks Regarding the Integration of Turbojets and Ramjets*

The integration of these two systems is difficult and is often fraught with complexities and problems of all sorts. Some of these include:

- As the vehicle reaches Mach 1, the turbojet engines are shut off and the ramjet engine(s) is/are ignited. The small-time delay in ignition of the ramjets and shutting down the

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turbojets can cause a decrease in the velocity of the vehicle. Although this decrease may not be appreciable in many cases, sometimes the retardation provided can force the air intake velocity of the ramjets to decrease well below its requirement, which is far from ideal. This error will require a difficult course of rectification mid-flight, involving starting up the turbojet engines once more, accelerating past Mach 1 and attempting a re-ignition of the ramjets, using up fuel in the process.

- According to Bernoulli's principle, as the velocity of a fluid increases, its pressure decreases. Conversely, a decrease in the fluid velocity can result in a drop in pressure. As discussed above, the vehicle's retardation as a result of an erroneous time delay between the transition of the turbojet and ramjet engines forces the air intake velocity to suddenly decrease, causing a rapid increase in pressure. This rapid increase in pressure is especially deleterious to the components of the turbojet engine(s). The turbojet relies on compressors and turbines, which are sensitive to back-pressure, and any abrupt change in airflow (and consequently, air pressure) can cause compressor stall. [5]

- Both turbojet and ramjet engines depend on carefully shaped air inlets to compress incoming air before combustion. However, turbojets require the air intake velocity to be well below Mach 1, while ramjets do not operate at all when the airflow is below supersonic speed. Designing a single inlet for the two engines is inherently complex. The resulting inlet nozzle should not only handle Mach flow regimes efficiently, but also prevent phenomena like "inlet unstart" (sudden flow reversal caused by improper shockwave placement). [6]

- Ramjet operation generates extremely high combustion temperatures, often exceeding 2000 K. While turbojets are already thermally stressed, the problem is more severe in ramjets due to longer exposure of internal components to intense heat. The lack of rotating components in ramjets further intensifies this problem, as the heat generated cannot be carried away, which results in thermal stagnation. Additionally, as ramjets are used in vehicles that have to travel at speeds that usually exceed the speed of sound, the heat generated due to air resistance on the external skin further exacerbates this problem. [7]

- By combining two propulsion systems in one missile or aircraft, the engine bay must accommodate both a turbojet and a ramjet, which results in an increased structural mass, reducing payload or fuel capacity. Additionally, these vehicles experience more aerodynamic drag due to larger frontal area and additional air ducting. Complex integration of multiple fuel lines, nozzles, and flow control systems result in increased cost and weight. This tradeoff in particular is critical for missiles, where range, speed, and maneuverability depend on having a high thrust-to-weight ratio and minimal drag. [8]

III. THEORETICAL ANALYSIS OF SOLUTIONS TO THE ABOVE PROBLEMS

➢ *Bypass Diverter Valves:*

Direct airflow around the turbine to ramjet combustion chamber at transition Mach. [9].

➢ *Variable-Area Nozzles:*

Allow matching of pressure ratios between turbojet and ramjet phases [9]

➢ *Transition Control Logic:*

Implement real-time onboard controllers.

➢ *Using Variable-Geometry Inlet Systems:*

Ramps and Shock Cones for Controlling Oblique and Normal Shock Formation [10]:

$$\tan\theta = 2\cot\beta \frac{M_1^2 (\sin\beta)^2 - 1}{M_1^2(\gamma + \cos 2\beta) + 2}$$

- *Use of Ablative Liners:*

Sacrificial layers in the ramjet combustion chamber burn away due to excess heat, but do not cause any critical failure(s) due to them lacking connection to any primary systems.

- *Implementing Regenerative Cooling:*

Circulate incoming fuel through walls before combustion to absorb heat[11]. This concept is similar to regenerative cooling in a liquid rocket engine using liquid hydrogen as a primary fuel.

- Using Thermal Barrier Coatings (TBCs)- Ceramics like yttria-stabilized zirconia are appropriate for high-temperature conditions [12].

- *Integration Tradeoffs:*

Minimize extra components by sharing inlet, nozzle, and fuel system [9]. Use lightweight alloys (e.g., titanium aluminides) and composite thermal shielding [13].

IV. INTEGRATION OF RAMJETS AND TURBOJET ENGINES

Assuming the solutions to all the problems listed above are solved, the main challenge to overcome will be successful integration and transition between the ramjet and turbojet stages.

Although our main aim is to integrate these two engines, their essential working systems and conditions are, as mentioned above, quite different.

A turbojet engine works on the principle of a Brayton cycle. The Brayton cycle is a thermodynamic cycle that describes the workings of a constant-pressure heat engine, such as those found in gas turbine engines, including turbojet engines used in aircraft propulsion. It is named after George Brayton, an American engineer who developed an early

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internal combustion engine based on this principle. The Brayton cycle consists of four key processes: isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection [14].

In a turbojet engine, the Brayton cycle is implemented through a series of components: the inlet, compressor, combustion chamber, turbine, and nozzle. Air enters the engine through the inlet and is compressed in the compressor section, which corresponds to the isentropic compression phase. As the air is compressed, its pressure and temperature rise significantly. This high-pressure air then flows into the combustion chamber, where fuel is injected and burned at constant pressure—this is the heat addition phase. The combustion produces high-temperature, high-pressure gas. These hot gases then expand through the turbine, where they perform work to drive the compressor—this is the isentropic expansion phase. After passing through the turbine, the remaining high-energy gases are expelled through a propelling nozzle, where they expand further to produce thrust. This final exhaust process corresponds to the heat rejection phase, although in open-cycle gas turbines like turbojets, heat rejection occurs indirectly as the exhaust gases are released into the atmosphere [14].

The efficiency of the Brayton cycle depends primarily on the pressure ratio across the compressor. Higher pressure ratios lead to greater thermal efficiency, meaning more useful work is extracted from the fuel. Modern turbojet and turbofan engines achieve pressure ratios of 30:1 or higher, significantly improving fuel efficiency and performance.

One of the main advantages of the Brayton cycle in turbojet engines is its ability to produce high thrust-to-weight ratios, making it ideal for aviation. Unlike piston engines, gas turbines operate smoothly at high speeds and deliver continuous power, which is essential for sustained flight. Additionally, the simplicity of the design—few moving parts and continuous combustion—contributes to reliability and durability.

➢ *The Graph (Temperature v/s Entropy) for a Brayton Cycle Engine is Given as:*

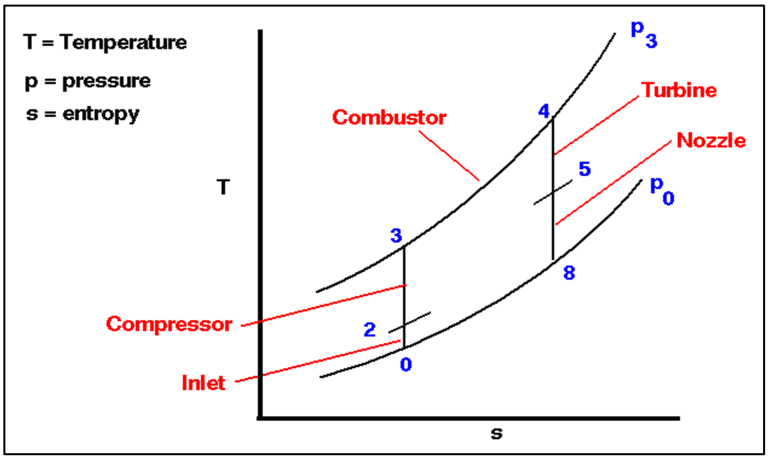

Fig 1 Temperature v/s Entropy Graph of an Ideal Brayton Cycle

Credit for Graph Image: [15]

A ramjet engine, however, is a type of air-breathing jet engine that relies on the forward motion of the engine to compress incoming air. It doesn't have any rotating parts like compressors or turbines, making it a relatively simple design. The high-speed airflow compresses the air as it enters the engine, and this compressed air is then mixed with fuel and ignited in the combustion chamber. The expanding exhaust gases provide the thrust to propel the engine forward.

As mentioned before, the velocity of airflow intake of these two engines varies greatly. For turbojet engines, the velocity of airflow must be subsonic, while for ramjets, it must be well above the speed of sound.

Ramjet combustion is modeled in a constant-area duct with compressive effects from oblique/normal shocks at the inlet. Combustion in the ramjet is treated as a Rayleigh heat-addition process (constant area), and the Rayleigh relations provide changes in stagnation properties due to the added heat. These are central to predicting the exhaust velocity, and thus, thrust [16].

V. TRANSITION BETWEEN TURBOJETS AND RAMJETS IN A TBCC

The integration and transition of these two stages in a single aerial vehicle is governed by the following relation:

$$F_{hybrid}(M) = F_{TJ}(M),\ M < M_t$$

$$F_{RJ}(M),\ M \geq M_t$$

Here, Mt is the mach transition number, and for smooth transition between the two stages, it is imperative that they overlap. [17]

The transition, unfortunately, is where most of the problems begin to concentrate. For smooth transition and little to no dip in the Mach number during it, one must balance the following three conditions:

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- Mass-flow continuity across splitters. There should be an even flow of propellant and air in an ideal ratio for combustion at all times, even during transition. This, however, poses significant challenges, requiring complex analysis and manufacturing of new, costly, and heavy redistribution systems. This reduces overall efficiency.

- Total-pressure / total-temperature compatibility at the point where flows are redirected (inlet splitter/isolator). If the turbine exhaust back-pressure is too high compared to the ramjet inlet total pressure, the turbine will stall or windmill.

- Power balance on the turbine/compressor spool (dynamic): the turbine must produce the compressor work until the turbo core is shut down.

(Reference(s): *[17]*

Additionally, when one moves from turbo to ram mode, there is a transient minimum, because the turbojet is being slowly starved of air, and thus, oxygen. Due to this, the turbojet cannot continue combustion, as the air is now diverted toward the ramjet engine. However, the ramjet itself has not reached full thrust yet, and the time period in between which the turbojet engine's air supply is cut off and the ramjet begins to start up is marked by a dramatic drop in overall thrust produced.

One can, however, characterize the minimum thrust during transition by simulating time-dependent versions of the thrust equation with the transient spool model and with inlet pressure recovery as a function of splitter position s(t). Guo et al. showed that such a minimum can be a large fraction drop (e.g., down to 20–30% of pre-transition thrust in some simulations), unless controlled. [16]

The solution for the given problem is, however, in theory, fairly simple. As discussed above, the manufacture of variable geometry for inlet systems will help mitigate many of the problems brought about due to the abrupt transition of mach numbers (s) of the air flow intake (refer above).

Adding a small high-thrust, short-duration booster (rocket or ejector) or keep the turbo in "windmilling" will produce some residual thrust until ramjet reaches steady operation — this mitigates thrust trap and is used in some TBCC concepts (XTER, rocket-augmented TBCC).[18]

- *Transition Design:*

The crossover region reveals the most sensitive Mach range — TBCC control systems must execute seamless mode switching here to avoid a temporary loss in specific impulse or thrust dip.

- *The Transition is Given by the Following Equation:*

$$F^{TJ}{}_{max}(M_t, h) = F^{RJ}{}_{max}(M_t, h)$$

- *Symbology:*

✓ $F^{TJ}{}_{max}$: Maximum thrust produced by the Turbojet at a given flight Mach number M_t and height *h*.

✓ $F^{RJ}{}_{max}$: Maximum thrust produced by the Ramjet at a given flight Mach number *M* and height h.

Reference(s): *[19]*

- *The Combined Schematic for a TBCC Can be Drawn as follows:*

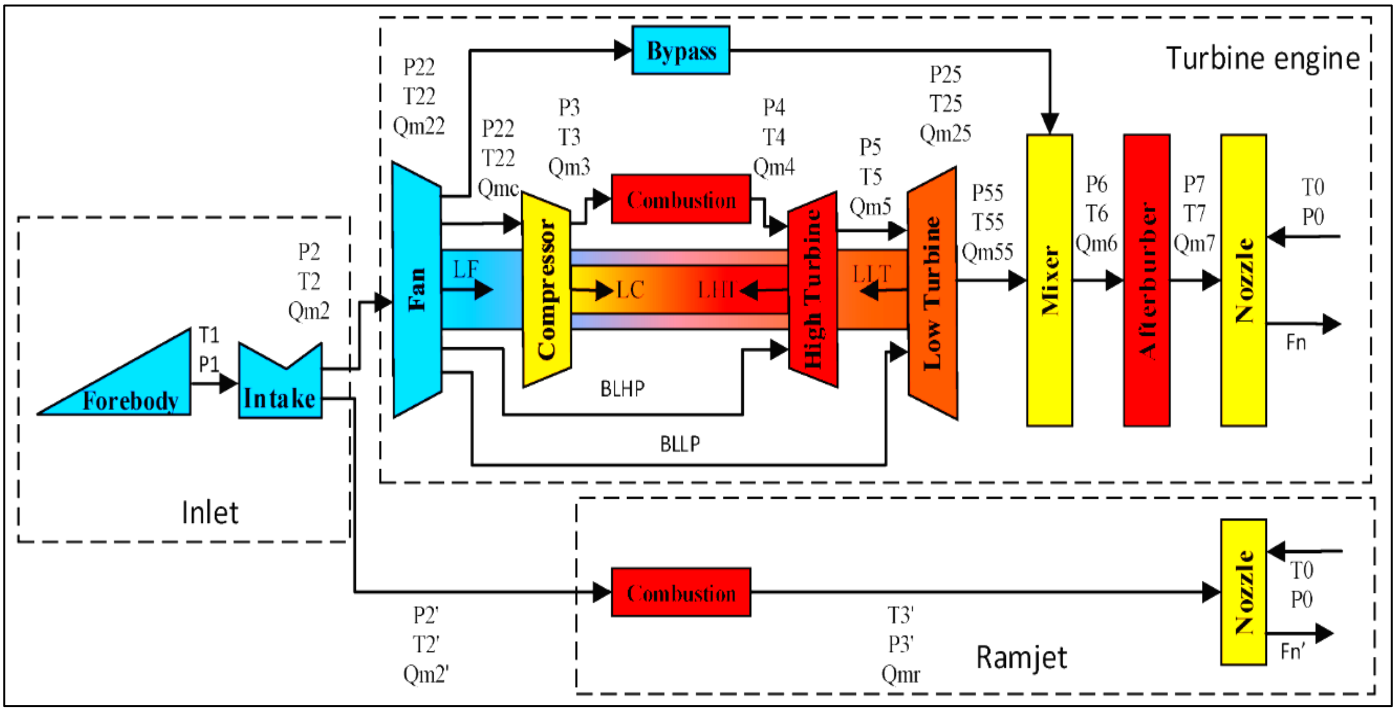

Fig 2 Is the Schematic of an Integrated Turbojet and Ramjet Cycle Engine.

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Credit for image: *[20]*

The transition between the two stages is accompanied by a number of other changes in the integrated systems.

➢ *Some of These Changes Include:*

- *Throttle and Bypass Control:*

In Turbine-Based Combined Cycle (TBCC) engines, throttle and bypass control are crucial for managing airflow and thrust during mode transitions (here, from turbojet to ramjet) and throughout the flight envelope. Throttle controls the fuel flow and thus the power output of the engine, while bypass control regulates the airflow through different engine paths (core and bypass) to optimize performance at various speeds and altitudes. The compressor stages are shut off and the fuel flow is directed in greater amounts toward the ramjet for greater performance. [21]

- *Fuel Management:*

The concentration of fuel used in both engine systems also varies. Turbojet engines use a lean mix throughout operation, while ramjets use a rich mixture for cold starts and rapid acceleration. Ensuring optimal combustion ratio in both cases is vital. [22]

- *Combustion Stability:*

Combustion instability, also known as thermoacoustic instability, is an undesirable phenomenon where pressure fluctuations within a combustor amplify due to the interaction between acoustic waves and unsteady heat release. This feedback loop can lead to sustained, high-amplitude oscillations, potentially causing structural damage. TBCC engines are designed to operate efficiently across a wide range of speeds and altitudes by transitioning between different modes, such as turbojet, ramjet, and possibly rocket modes. The transition between these modes involves significant changes in the combustion environment, including variations in airflow, fuel injection, and temperature. These rapid changes can result in combustion instability, potentially damaging the structural integrity of the engine. [22]

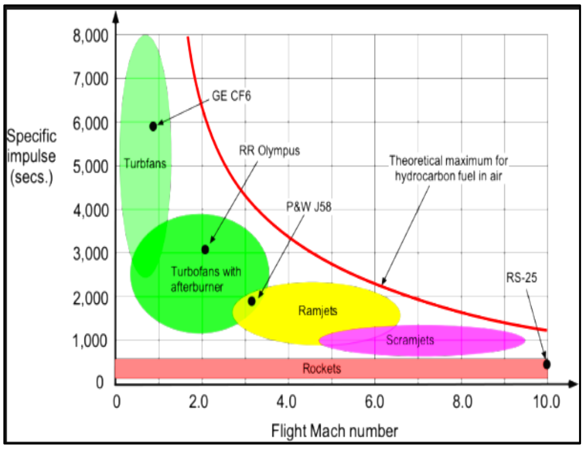

Fig 3 Displays Specific Impulse v/s Mach Number Graph of Various Supersonic Engines

Credit for image: *[23]*

VI. COMBINED CYCLE (TBCC) THRUST OUTPUT POST-INTEGRATION

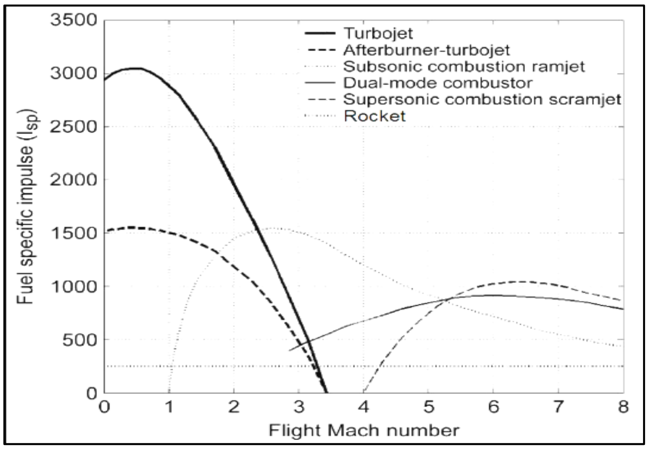

Fig 4 Presents Specific Thrust (Thrust Per Unit Mass Flow) Plotted Against Mach Number for Several Propulsion Cycles — Typically Including Turbojet, Ramjet, and Combined Variants.

Image source: *[24]*

➢ *Subsonic to Low Supersonic (Mach 0–2):*

The turbojet curve rises, reaching peak specific thrust around transonic speeds. This reflects the turbojet's strength: its compressor delivers significant pressure rise, enabling high exhaust velocities with acceptable fuel flow.

➢ *High Supersonic (Mach 2–5):*

The ramjet curve begins near zero at low Mach (inefficient startup) but climbs steeply in the supersonic regime. This demonstrates the ramjet's reliance on high inlet dynamic pressure for compression and its ability to produce high specific thrust when already at speed.

➢ *Combined-Cycle TBCC:*

A TBCC curve would trace the turbojet line at low Mach, then smoothly transition to the ramjet performance at higher Mach. The point where specific thrust curves cross is the transition Mach number (M_t). This design ensures high performance across a wide range.

This is important as it visually encapsulates the performance envelopes of each mode and underscores why TBCC is attractive for supersonic/hypersonic vehicles. Turbojets cover launch and transonic climb; ramjets cover sustained supersonic cruise; TBCC offers the best of both, provided the mode transition is handled without a thrust dip ("thrust trap", as mentioned above).

(Reference(s): *[24]*

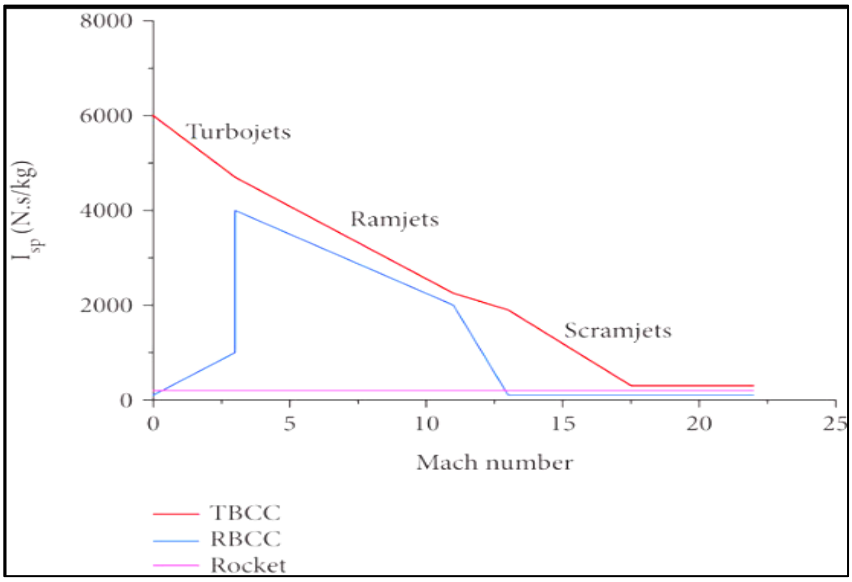

Fig 5 Compares Specific Impulse (I_{sp}) — A Measure of Fuel Efficiency — for Turbojet, Ramjet, and Combined-Cycle Engines Across Increasing Mach Numbers

Image source: *[25]*

➢ *Turbojet:*

I_{sp} decreases gradually as Mach increases. This is due to the increasing kinetic energy of the incoming air (raising compression requirement), and fixed turbine temperature limits which reduce thermal efficiency.

➢ *Ramjet:*

I_{sp} is very low at low Mach (since flame zones aren't sustained), but increases rapidly beyond Mach ~2–3 as inlet compression improves and combustion is more efficient at high dynamic pressure. Its specific impulse surpasses turbojet in high supersonic regimes.

➢ *TBCC Curve:*

A well-designed TBCC engine maintains the turbine's better impulse at low speeds, then transitions to the ramjet's higher impulse at supersonic speeds, yielding an I_{sp} envelope that remains near optimum across the flight envelope *[25]*

➢ *Significance:*

- *Fuel Efficiency:*

I_{sp} is thrust per unit fuel flow, so a higher value means longer range or smaller fuel mass for the same mission. TBCC leverages this by "choosing" the most efficient engine mode for each speed.

- *Operational Flexibility:*

This curve clearly illustrates why neither turbojet nor ramjet alone covers the full mission. TBCC blends dual regimes to maintain efficiency.

VII. CONCLUSION

Theoretical analysis of a Turbine-Based Combined-Cycle (TBCC) propulsion system discloses the potential and challenges of combining turbojet and ramjet engines under a single architecture for supersonic missile use. Through comprehensive consideration of thrust performance, Rayleigh flow relationships, transition criteria, and maximum thrust derivations, the research confirms that the underlying crossover point—where turbojet peak thrust is equal to ramjet peak thrust—is the most significant design limit in combined-cycle propulsion. This equality not only prescribes the operational Mach number range of every propulsion mode but also emphasizes the engineering challenge of smooth mode transition.

The analysis points out that turbojets are best suited for subsonic to low-supersonic regimes because they can mechanically compress ingested air, whereas ramjets are more efficient in the higher supersonic regime by taking advantage of shock-compression and not turbine temperature restrictions. The resulting thrust equations, backed by Rayleigh flow theory, highlight how altitude-Mach number dependence is the rule for engine performance within flight regimes. Further, parametric relationships and performance plots indicate that transition control measures—like inlet control, thermal control, and fuel-air mixing stability—are key to real-world implementation.

From a system point of view, the TBCC arrangement provides a route to small, efficient, and mission-configurable propulsion for long-range, high-speed missile flight without reliance on rocket propulsion for extended cruise. But the theoretical results also suggest inherent issues like thermal loading, transition inlet matching, and high Mach number combustion stability, all of which require creative engineering solutions.

Under idealized assumptions, the analysis suggests that the energetic crossover favoring ramjet operation occurs near Mach 3, where the thermal efficiency and thrust-to-fuel ratio of ramjet propulsion exceed those of turbojet operation. This transition is not abrupt but occurs over a finite Mach range, supporting the viability of combined-cycle architectures—such as turbojet-based combined-cycle (TBCC) engines—that exploit turbojet efficiency at lower Mach numbers while transitioning to ramjet dominance at higher supersonic speeds.

In summary, the TBCC system is a technologically viable but difficult solution to attaining wide operational ranges in supersonic missile design. Although the current paper proposes a theoretical model of thrust prediction, transition dynamics, and performance analysis, more studies should couple computational fluid dynamics (CFD), high-enthalpy wind tunnel tests, and materials innovation to verify and calibrate these models.

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