# Thermodynamic Cycle of Intake-Precooled Fuel-Rich Preburner Mixed-Flow Turbofan Engine Postprint

**Authors:** Zhao Wei, Zhao Qingjun, Jianzhong Xu

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## Abstract

To meet the requirements of hypersonic vehicles for high specific impulse and high thrust engines, a reusable thermodynamic cycle for an inlet pre-cooled fuel-rich pre-burned mixed-flow turbofan engine (Pre-cooled and Fuel-rich Pre-burned Mixed-flow Turbofan, PFPMT) is proposed. The PFPMT engine is characterized by increasing the degree of inlet pre-cooling of the core airflow; the core compressor provides air to the fuel-rich gas generator as an oxidizer; the core air mixes and combusts with fuel at the pre-cooler exit to produce fuel-rich gas, driving the turbine, which in turn drives the core compressor and fan for compression; the fan bypass air mixes and combusts with the turbine exit exhaust in the main combustor, generating high-temperature gas that produces thrust through the nozzle. A parametric analysis of the engine thermodynamic cycle was conducted: the engine specific impulse increases with the compressor pressure ratio, particularly more significantly with the fan pressure ratio; the specific thrust increases primarily with the fan pressure ratio and is less affected by the core pressure ratio. The engine' s ground-level specific impulse and specific thrust can reach above 4500 s and 900 N · s/kg, respectively; under flight conditions of Mach 5.0, the engine specific impulse and specific thrust are above 3500 s and 1100 N · s/kg, respectively.

## Full Text

## Preamble

### A Pre-cooled and Fuel-rich Pre-burned Mixed-flow Turbofan Cycle

Wei Zhao[1],[2], Qingjun Zhao[1],[2],[3], Jianzhong Xu[1]
[1]Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[2]University of Chinese Academy of Sciences, Beijing 100190, China

[3]Key Laboratory of Light-duty Gas-turbine, Chinese Academy of Sciences, Beijing 100190, China

## Abstract

A Pre-cooled and Fuel-rich Pre-burned Mixed-flow Turbofan (PFPMT) cycle is presented for reusable hypersonic vehicles based on practical technologies. PFPMT uses an inlet hydrogen precooler to reduce the inlet temperature for a core flow compressor and thus reduces the compression work for a given pressure ratio. The core flow compressor provides pressurized air for a fuel-rich gas generator to burn with the warmed hydrogen from the precoolers. The gas from the gas generator is introduced to a turbine to drive the core flow compressor and a bypass flow fan. The exhaust of the turbine is mixed with the bypass flow in a combustor at an equal total pressure, and is ignited. The high temperature combustion products are expanded in a nozzle to generate thrust. The emphasis in this work is on the analysis of the design parameters for feasible PFPMT. Parametric studies are performed with the following parameters: 1) the bypass ratio; 2) the core flow fuel ratio, which is defined as the core flow mass over the fuel mass; 3) the core compressor pressure ratio; and 4) the bypass fan pressure ratio. The cycle simulation results for a PFPMT engine show that on the ground the specific impulse and specific thrust are greater than 4965s and 944 N/(kg/s) respectively. At the flight Mach number of 5.0 the specific impulse and specific thrust are greater than 3500s and 1100 N/(kg/s) respectively.

**Keywords:** hypersonic flight; engine cycle; parametric analysis; fuel-rich combustion; inlet precool

## 0 Introduction

Hypersonic vehicles hold significant promise for enabling rapid long-distance transportation systems [?]. Over the past several decades, researchers have explored various combined-cycle engines for supersonic flight, including the Gas Generator Air Turbo-Rocket (ATR GG), Expander Air Turbo-Rocket (ATR EX), and SABRE. The ATR GG consists primarily of a fan, a high-pressure fuel-rich gas generator, and a turbine, typically employing bipropellant propellants including fuel and oxidizer. This engine configuration offers high thrust-to-weight ratio but relatively low specific impulse [?]. The ATR EX utilizes a combustion chamber heat exchanger to replace the gas generator of the ATR GG, heating fuel to drive the turbine. Combined with inlet precooling, the engine can operate up to a maximum Mach number of 6 [?]. This engine obtains oxidizer from the atmosphere, achieving higher specific impulse but lower thrust-to-weight ratio compared to ATR GG. The SABRE engine precools inlet air to cryogenic temperatures before it enters a high-pressure-ratio compressor;

the compressor discharge splits between the main combustion chamber and a fuel-rich preburner, with high-temperature fuel-rich gas discharged from the preburner to heat helium working fluid through a heat exchanger. The heated helium drives the turbine that powers the air compressor, after which it enters another heat exchanger to be cooled by cryogenic liquid hydrogen fuel. The fuel-rich gas then enters the main combustion chamber to mix and burn with air, with high-temperature combustion products exhausted through the nozzle to generate thrust [?]. The SABRE engine involves multiple working fluids and complex structures, making it difficult to implement.

This paper proposes a thermodynamic cycle for a Pre-cooled and Fuel-rich Preburned Mixed-flow Turbofan (PFPMT) engine capable of horizontal takeoff and operation to hypersonic speeds without mode transition. The PFPMT engine requires no onboard oxidizer, features no heat exchangers in the combustion chamber, and eliminates the complex helium intermediate cycle, thereby offering favorable specific impulse and thrust-to-weight ratio.

## 1 Cycle Description

The PFPMT engine cycle flow path resembles that of a turbofan engine, but its design intent primarily addresses the low specific impulse issue of ATR GG. In ATR GG, oxidizer and fuel undergo fuel-rich combustion in the gas generator to produce high-temperature fuel-rich gas that drives the turbine, resulting in relatively low engine specific impulse. If the ATR engine oxidizer could be sourced entirely from the atmosphere, engine specific impulse would improve significantly.

In ATR GG engines, to achieve pressure balance between the compressor and turbine exit, high-pressure pumps are required to deliver oxidizer to the fuel-rich gas generator upstream of the turbine. The fuel-rich gas generated by the high-pressure gas generator represents a small fraction of compressor air flow; for methane fuel, the fuel-air ratio ranges from 1/8 to 1/6. Due to the relatively low fuel-rich gas flow rate, turbine expansion ratio is typically high, generally 15–25, resulting in high gas generator outlet pressure. If turbine expansion ratio could be reduced, gas generator chamber pressure and fuel pump pressure ratio could be lowered, potentially enabling replacement of the fuel pump with an air compressor to supply the oxidizer required by the engine, thereby improving specific impulse. Two considerations support this approach: First, when turbine inlet temperature is fixed, employing a fuel-rich preburner increases fuel-rich gas flow, thereby reducing turbine expansion ratio and inlet pressure. This allows increased turbine blade height and reduced secondary flow and tip leakage losses. Second, employing a liquid hydrogen inlet precooler reduces fan and compressor inlet temperature, decreasing compression work and thus lowering turbine expansion ratio. These two measures enable turbine expansion ratio reduction such that the required turbine inlet pressure can be achieved with few compressor stages. An additional benefit of reduced turbine expansion ratio is fewer turbine stages, thereby increasing engine thrust-to-weight ratio.

Based on this understanding, the PFPMT thermodynamic cycle flow is established as shown in Figure 1. Two liquid hydrogen/air precoolers are installed in the inlet as precooling devices, one at the fan bypass inlet and the other at the core inlet. The core compressor pressurizes incoming air, whose discharge mixes and burns with fuel from the precooler outlet in the gas generator to produce fuel-rich gas that drives the turbine powering both the fan and core compressor. Turbine exhaust mixes with fan bypass discharge in the main combustor for mixed combustion, with high-temperature combustion products exhausted through the nozzle to generate thrust. In this cycle, core compressor outlet pressure equals the product of turbine expansion ratio and fan pressure ratio. The PFPMT cycle flow demonstrates that this cycle requires no onboard oxidizer and will achieve significantly higher specific impulse than the ATR GG cycle.

[Figure 1: see original paper]

## 2 Component and Cycle Models

Understanding PFPMT engine basic performance requires establishing working fluid, component, and thermodynamic cycle models.

### 2.1 Working Fluid Model

Working fluid thermophysical properties such as enthalpy and entropy are composition-dependent. Air consists of 21% O and 79% N. Gas generator and combustor product compositions primarily include: H, O, OH, HO, H O, H O, N, NO, N, H, and O. Given pressure and oxidizer-to-fuel ratio, combustion products are calculated using a chemical equilibrium method based on minimization of Gibbs free energy. Turbine and nozzle working fluids are assumed to be frozen flow, with component enthalpies obtained from high-order polynomials.

### 2.2 Inlet

Free-stream air decelerates through the inlet, with static temperature and static pressure determined as follows:

Given flight altitude and Mach number, inlet total temperature and total pressure are:

Exit total pressure:

### 2.3 Precooler

Precoolers control fan and core compressor outlet temperatures within material limits, using incoming air to preheat fuel while improving flow matching performance between the inlet and compressors. Given precooler heat exchanger effectiveness and fuel-air ratio, precooler cold-end and hot-end outlet temperatures are obtained based on energy conservation:

### 2.4 Fan and Core Compressor

The fan and compressor provide pressure rise in the PFPMT cycle. Given compressor pressure ratio, enthalpy increase during the isentropic process is calculated by:

Compressor actual work consumption is calculated using compressor efficiency:

With efficiency given, fan and compressor outlet enthalpy is:

Air total temperature is a function of enthalpy and total pressure:

Turbine output power balances fan and compressor power consumption, with turbine outlet enthalpy:

Assuming turbine efficiency, turbine outlet enthalpy under isentropic conditions is:

Based on isentropic turbine outlet enthalpy and turbine inlet entropy, turbine expansion ratio is:

From calculated turbine outlet pressure and temperature, working fluid thermophysical properties at the turbine exit plane are obtained.

### 2.5 Preburner and Main Combustor

The preburner and main combustor employ fuel-rich and fuel-lean combustion respectively, using identical combustion models. Fuel-air mixture ratio is obtained from fuel and air flow rates, then mixed gas specific enthalpy is calculated based on fuel-air ratio. Chemical equilibrium in the preburner and main combustor is calculated based on constant enthalpy and pressure principles, with reaction product composition and thermophysical parameters obtained through minimization of Gibbs free energy.

### 2.7 Nozzle

The nozzle accelerates combustor high-temperature gas, expanding it to ambient pressure to efficiently generate thrust. Nozzle throat and exit areas are assumed adjustable, expanding ideally to ambient pressure. Velocity loss coefficient (ratio of actual velocity to isentropic expansion velocity) is used to calculate nozzle losses:

### 2.8 Cycle Model

Based on the PFPMT engine thermodynamic cycle structure described above, component models are assembled into an engine thermodynamic cycle mathematical model. Working fluid flow rates balance at component inlets and outlets, with identical thermophysical properties at interfaces between adjacent components. To ensure mixing feasibility between fan bypass exit air and turbine exit gas, exhaust exit total pressure is maintained equal.

Based on energy conservation equations in component models, flow conservation equations between components, and pressure balance relationships between fan bypass and turbine exit, a nonlinear equation determining fan bypass ratio is obtained. By selecting fan pressure ratio, core compressor pressure ratio, or fuel-air ratio in core or bypass precoolers as design parameters, preburner and main combustor exit temperatures can be solved:

An iterative solution method is employed, requiring initial values for variables first. A Matlab mathematical model for working fluid, components, and engine thermodynamic cycle was developed using the Cantera interface. Nonlinear equation sets in the cycle are solved using Matlab built-in algorithms.

### 2.9 Performance Calculation

Engine specific thrust Fs is uninstalled thrust:

Through thermodynamic cycle model calculation of nozzle exit velocity Vout, engine specific thrust Fs and specific impulse ISP are obtained.

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## 3 Cycle Parametric Analysis

Cycle parametric analysis primarily investigates how working fluid thermophysical property variations reveal the influence of cycle parameters on design-point cycle performance under different flight conditions. Selected PFPMT cycle parameters include: 1) fan pressure ratio f ; 2) core compressor pressure ratio C ; 3) fan precooler fuel-air ratio f ; and 4) core compressor precooler fuel-air ratio C . Unlike traditional high bypass ratio separate-flow turbofan engines, bypass ratio is not a cycle parameter because it can be determined through the above four cycle parameters and fan-turbine exit pressure balance conditions. Component parameter values during analysis are shown in Table 1.

Figures 2a–2e show ground condition variations of bypass ratio, gas generator outlet temperature, combustor outlet temperature, engine specific impulse, and thrust with core pressure ratio at different fan pressure ratios.

In Figure 2a, bypass ratio increases with core pressure ratio at a given fan pressure ratio. Since fan bypass total pressure balances turbine exit total pressure, turbine expansion ratio equals the quotient of core compressor pressure ratio and fan pressure ratio. Therefore, with constant fan pressure ratio, turbine expansion ratio increases proportionally as core pressure ratio increases. Since turbine inlet temperature is much higher than core compressor inlet temperature, turbine output work increment exceeds core compressor consumption work increment as seen in Equation (27). At this point, fan bypass air flow must increase to consume excess turbine work, increasing engine bypass ratio.

At a given core compressor pressure ratio, constrained by fan bypass-turbine exit pressure balance, bypass ratio increases while turbine expansion ratio decreases as fan pressure ratio decreases. With core compressor operating conditions unchanged, excess turbine output work must be balanced by increasing fan consumption work. With decreasing fan pressure ratio, bypass ratio increases to achieve higher fan consumption work. Therefore, bypass ratio increases as fan pressure ratio decreases.

Figure 2b shows that at constant fan pressure ratio, turbine inlet temperature decreases as core compressor pressure ratio increases. At constant core compressor pressure ratio, turbine inlet temperature increases as fan pressure ratio increases. As described above, increasing core compressor pressure ratio or decreasing bypass fan pressure ratio increases fan flow and bypass ratio. Since bypass fuel-air ratio is constant, fuel flow into the gas generator increases with bypass ratio, decreasing fuel-rich gas total temperature.

Figure 2c shows main combustor outlet temperature trends mirror preburner outlet temperature trends, explainable through bypass ratio variations. In this analysis, bypass fuel-air ratio is approximately half the core fuel-air ratio; if bypass ratio increases, main combustor fuel-air ratio necessarily decreases, leading to lower combustor outlet temperature.

When core pressure ratio exceeds 5, engine thrust is minimally affected by core pressure ratio changes. Since core pressure ratio greater than 5 corresponds to bypass ratio greater than 2.5, fuel-air ratio and main combustor temperature are primarily influenced by bypass fuel-air ratio changes rather than core fuel-air ratio changes. Therefore, at high bypass ratios, core compressor pressure ratio has minimal impact on specific thrust. Fan pressure ratio increase, however, rapidly increases engine specific thrust. As described above, increasing fan pressure ratio raises both combustor outlet temperature and nozzle inlet total pressure, both factors increasing engine thrust for a given ingested air flow rate.

Figure 2e shows engine specific impulse increases with both core compressor pressure ratio and fan pressure ratio. As analyzed above, increasing core compressor pressure ratio leads to increased bypass ratio and decreased combustor temperature, increasing engine specific impulse. Although increasing bypass pressure ratio decreases bypass ratio and increases combustor temperature, nozzle total pressure increases, raising engine specific impulse.

Figure 2e shows engine specific impulse increases with core pressure ratio. Specific impulse can be expressed as:

Since bypass ratio increases with core compressor pressure ratio and bypass fuel-air ratio is less than core fuel-air ratio, cycle fuel-air ratio decreases as core compressor pressure ratio increases. Note that specific thrust is insensitive to core compressor pressure ratio, thus engine specific impulse increases with core compressor pressure ratio. Figure 2e also shows that maximum specific impulse is achieved when f = . This occurs because under C = conditions, engine specific thrust increases rapidly while engine fuel-air ratio decreases slowly as fan pressure ratio increases. When core compressor pressure ratio exceeds 5, fan bypass ratio exceeds 2.5, and engine fuel-air ratio is primarily influenced by bypass fuel-air ratio. When core compressor pressure ratio exceeds 5, engine specific impulse increases with fan pressure ratio.

For flight conditions of Mach 5.0 at 27 km altitude, component and cycle parameters versus core total pressure at different bypass fan pressure ratios are shown in Figures 3a–3e. Except for specific impulse, bypass ratio, gas generator outlet temperature, combustor outlet temperature, and specific thrust show trends consistent with Figure 2. At Mach 5, inner and outer bypass pressure ratios and their difference decrease significantly, with inner and outer bypass fuel ratios becoming more similar to Ma0 conditions. This makes cycle fuel-air ratio less sensitive to bypass ratio, with specific thrust essentially independent of outer bypass pressure ratio changes. Since fuel-air ratio is proportional to outer bypass pressure ratio, specific impulse, as the ratio of specific thrust to fuel-air ratio, decreases with outer bypass fan pressure ratio.

Based on understanding of interrelationships among cycle parameters, Table 2 presents favorable PFPMT cycle parameters at flight speeds of Ma0, 3, and 5. Both inner and outer bypass pressure ratios decrease with increasing flight Mach number, while f increases significantly to reduce outer bypass fan outlet temperature and turbine inlet temperature to material-allowable levels. Despite this, low-temperature hydrogen steam film cooling is still required when flight Mach number exceeds 4. Due to increased f , combustor outlet temperature rises significantly, helping prevent specific thrust decay at high flight Mach numbers. At Mach 5, although specific impulse decreases 20% compared to ground Ma0 conditions, PFPMT still demonstrates clear advantages over ramjet engines which achieve approximately 3000s specific impulse at Mach 5.

[Figure 2: see original paper]

[Figure 3: see original paper]

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## 4 Conclusions

1) PFPMT thermodynamic cycle analysis demonstrates that the PFPMT engine can achieve horizontal takeoff from ground to hypersonic flight with favorable specific impulse performance. Compared with complex thermodynamic cycles such as SABRE and Simitar, PFPMT’ s outstanding ad-

vantage is reduced system complexity, absence of mode transition devices, and elimination of intermediate thermodynamic cycles employing a third working fluid, enabling significant improvement in engine thrust-to-weight ratio.

2) Parametric PFPMT thermodynamic cycle analysis clarifies the influence of component design variables on engine performance and component parameters, effectively guiding overall performance design of PFPMT engines meeting specific impulse and thrust requirements under various flight conditions. Engine specific impulse increases with compressor pressure ratio, particularly more noticeably with fan pressure ratio; specific thrust primarily increases with fan pressure ratio, being less affected by core pressure ratio increases.

3) At a given bypass fan pressure ratio, PFPMT bypass ratio increases with core pressure ratio; at a given core pressure ratio, PFPMT bypass ratio decreases with bypass fan pressure ratio. Increased bypass ratio leads to decreased turbine inlet temperature and combustor outlet temperature, reducing specific thrust while existing optimal bypass fan pressure ratio maximizes specific impulse.

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