Energy 154 (2018) 96–109

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance analysis of a pre-cooled and fuel-rich pre-burned mixed-flow turbofan cycle for high speed vehicles

Wei Zhao [a, b], Chen Huang [a, b], Qingjun Zhao [a, b, c, *], Yingqun Ma [a, b], Jianzhong Xu [a, b]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, 100190, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Key Laboratory of Light-duty Gas-turbine, Chinese Academy of Sciences, Beijing, 100190, China

ARTICLE INFO

Article history:
Available online 20 April 2018

Keywords:
Inlet precooling
Fuel-rich pre-burner
Air-breathing engine
Combined cycle
High speed propulsion

ABSTRACT

A novel Pre-cooled and Fuel-rich Pre-burned Mixed-flow Turbofan (PFPMT) cycle is presented for reusable high speed vehicles based on practical technologies to reduce the travelling time of long distance flights. The motivation and the working principle of the PFPMT are explained in detail. A performance simulation model for the PFPMT cycle is established with the assumption of equilibrium fuel rich gas as the working fluid in the gas generator. Then parametric cycle studies are performed with the variation of bypass ratio, fuel/air ratio, core compressor pressure ratio and bypass fan pressure ratio at the flight Mach number of 0 and 5 respectively. The interrelationships between cycle parameters and their effects on cycle performance are discussed. Based on the parametric analysis, cycle parameters for a practical PFPMT engine are suggested for the flight speeds of Mach 0, 3 and 5 respectively. The predicted engine performance shows that the PFPMT concept exhibits a competitive specific impulse with respect to an ATR GG engine and an enhanced thrust to weight ratio with respect to an ATREX engine, and might be a promising propulsion system for high speed air-breathing flying vehicles.

1. Introduction

High speed flights that can achieve intercontinental travelling within a few hours in supersonic vehicles are attractive for human being [1]. Turbine based combined cycle (TBCC) engines are promising propulsion systems to meet the requirements of such supersonic flights due to their horizontal take-off capability and high specific impulse potential in the flight envelop.

Various turbine based combined cycles for supersonic flights have been presented and considerably investigated in the past decades. ATR GG (Gas Generator) employs a modest pressure ratio fan, a high pressure fuel-rich gas generator and turbine to offer high thrust-to-weight ratio and good performance at high flight Mach numbers. It usually uses two propellants, a fuel and an oxidizer [2]. The use of a solid-fuel gas-generator ATR can reduce the flight time of a turbojet-powered vehicle by about one-third for the same total range, and can double the range and flight time of an equal volume solid rocket motor powered vehicles [3]. The off-design behavior of the ATR GG is recognized to be very sensitive to flight conditions. Different operating lines for each flight Mach number on the flight path can be found [4]. ATR EX (Expander), the other variant of ATR, replaces the gas generator of ATR GG by a heat exchanger in a burner to increase the fuel temperature to drive a turbine. All the oxidizer in the burner comes from the oxygen in air, and then the specific impulse is significantly increased. With inlet precooling the maximum flight velocity may exceed Mach 6 [5]. ATRDC (Deeply Cooled Air Turbo Rocket) engine employs deep air precooling by the use of ATR EX cycle and hydrogen fuel. It includes an inlet air precooler, compressor, combustion chamber and hydrogen heater. ATRDC should be integrated with a ram/scramjet to utilize the excessive hydrogen in its combustion chamber, so that the hydrogen not only precools the ATRDC inlet air, drives a turbine, combusts in the ATRDC chamber, but also combusts in the ram/scramjet chamber to generate extra thrust [6]. A propulsion fluid system known as ACES (Air Collection and Enrichment System) acquires and stores liquid oxygen for rocket use beyond the air breathing envelops. It avoids the need for carrying liquid oxygen at take-off and exhibits the performance of scramjets in the hypersonic regime without having to rely on scramjet function [7].

With the key technologies accumulated in the development of

---

[*] Corresponding author. Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, 100190, China.
E-mail address: zhaoqingjun@iet.cn (Q. Zhao).

https://doi.org/10.1016/j.energy.2018.04.113
0360-5442/© 2018 Elsevier Ltd. All rights reserved.

Nomenclature

BPR	Bypass ratio
C	Heat capacity rate, W/K
F	Thrust, N
G	Mass flow rate, kg/s
g	Acceleration of gravity, m/s^2
H	Enthalpy, J/kg, Height
HE	Heat Exchanger
I	Impulse, s
k	Ratio of specific heat
Ma	Flight Mach number
P	Total pressure, Pa
R	Gas constant, J/(kg K)
S	Entropy, J/kg K
SLS	Sea level static
T	Total temperature, K
TIT	Turbine inlet temperature, K
V	Velocity, m/s
W	Power, W
γ	Fuel/air ratio
δ	Velocity loss coefficient
η	Efficiency
ζ	Fuel/oxygen ratio
π	Pressure ratio
σ	Total pressure recovery coefficient, P_{out}/P_{in}

Subscripts

0	Stagnation, freestream condition
c	Core flow compressor, cold side of heat exchanger
cc	Combustor Chamber
f	Bypass fan
h	Hot side of heat exchanger
g	Gas generator
i	Isentropic process
in	Inlet
m	Mechanical efficiency
n	Nozzle
out	Outlet
s, sp	Specific
t	Turbine

Acronyms/Abbreviations

PFPMT	Pre-cooled and Fuel-rich Pre-burned Mixed-flow Turbofan

ATR EX engines, a precooled-cycle hypersonic turbojet engine with Mach 5 cruising capability is proposed [8,9]. The high temperature inlet air at hypersonic flight and the exhaust nozzle wall are cooled with cryogenic liquid hydrogen. The heated fuel is supplied to a main-burner and an after-burner, where the combustion is fuel-lean and fuel-rich respectively. A new method for defrosting the precooler using jet impingement is also presented for this engine [10]. To deliver a high air breathing thrust/weight ratio with moderate specific impulse, SABRE engine is designed with the air in intake is cooled to very low temperature prior to entry into an air compressor. The compressed air is divided to flow through a main combustion chamber and a fuel rich pre-burner. The hot gas from the pre-burner passes through a heat exchanger to raise the helium temperature. The pre-burner gas then flows to the main combustion chamber to complete its combustion with the remaining air prior to expansion through the exhaust nozzle. The helium is expanded in the turbine to drive the air compressor, and is cooled by hydrogen delivered from the hydrogen pump [11]. The Scimitar precooled Mach 5 cruise engine is a derivative of the SABRE spaceplane engine [12]. The Scimitar features a variable cycle engine that combines a turbofan based cycle with an ATR cycle and use high-pressure helium as a heat and work transfer medium. Its turbofan based cycle operates from take-off to Mach 2.5. Between Mach 2.5 and Mach 5 the engine has the dual operation of an ATR with a ramjet burner in the bypass duct. A fuel-lean pre-burner is employed to consume fuel to maintain a constant helium turbine inlet temperature [13].

Hydrogen is highlighted as the best candidate for long range transportation with potentially zero emissions. Its use also poses challenges, such as cryogenic liquid storage and efficient air/hydrogen heat exchange systems. Various applications for hydrogen fueled engines have been successfully used for civilian transport and others are under development [14]. Liquid hydrogen fueled aircrafts seems to be more efficient and still remain advantageous from the point of view of weight with respect to kerosene fueled aircraft [15]. An exergy analysis of a scramjet is presented with two kinds of fuel: one with a direct H_2 injection and the other with an on-board kerosene reformer. The calculations are performed with a modular simulator for energy conversion processes developed by the authors' group [16]. Air-hydrogen heat exchangers to provide in-flight oxygen collection capability to a reusable or semi-reusable two-stages-to-orbit launcher in supersonic cruise are also investigated. Experimental study proves the feasibility of an air-hydrogen precooler with no leak and high performance, which is built in a lightweight material via currently available manufacturing techniques [17].

Parametric cycle analysis explores the engine capability from a big-picture perspective for new concept or unconventional engines, such as turbofan engine with interstage turbine burner [18,19], scramjet engine [20,21], pulse detonation engine [22], ATR engine and etc. [23]. The performances of Turbo-ramjet (TRJ) and air turbo ramjet engines including the gas-generator cycle (ATR GG), the hydrogen expander cycle (ATR EX), and the liquefied air cycle (ATR LA) engines are discussed and compared. Although the thrust differences between these engines are little and the I_{sp} of the ATR GG is the lowest of all, the ATR GG has the advantage in the space plane propulsion system because its high thrust-to-weight ratio outbalances the low I_{sp} [24]. The variation and magnitudes of predicted ATR specific impulse as a function of oxygen to fuel ratio vary considerably depending on whether an ideal or equilibrium turbine gas is assumed. The major reason for this difference is that the fuel rich gas to drive a turbine is a reacting gas mixture, which does not behave as an ideal gas. In particular, when using either O_2/H_2 or O_2/propane propellants in an ATR the fuel rich gas should not be assumed to behave ideally [25]. The capabilities of ATR EX are assessed through a theoretical study of the thermodynamic cycle [26]. Parametric analyses are carried out to evaluate the performance and identify design trade-off compromises. The cycle is also optimized for the acceleration phase of an antipodal hypersonic vehicle fueled by hydrogen. Performance analysis is performed for a propulsion plant that consists of an ATR EX and a dual-mode ramjet. The transition of the air turbo-rocket to ramjet operation is identified at Mach 4.5 [27]. A numerical model of Scimitar is established to predict the engine performance [13]. The hypersonic Scimitar propulsion concept is also evaluated at flight Mach numbers ranging from 2.5 to 5 and variable throttling by means of