Applied Energy 220 (2018) 36–46

Contents lists available at ScienceDirect

Applied Energy

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

Overall performance design of paralleled heat release and compression system for hypersonic aeroengine

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HIGHLIGHTS

- The system is based on paralleled flow path and frequent heat transfer processes.
- System working principle, performance, and effects are studied for the first time.
- The system can dramatically improve the economy performance of the engine.
- The system can considerably reduce the difficulty of turbomachinery design.
- Future research directions and potential applications are summarized.

ARTICLE INFO

Keywords:
Hypersonic
Precooled engine
Innovative cycles
Overall performance analysis

ABSTRACT

The hydrogen powered hypersonic precooled combined cycle engine is an ideal candidate for next generation high speed clean civil aviation propulsion. It utilizes the energy inside the high speed air flow to power the air compression, in order to improve engine performance. Paralleled heat release and compression system, with several separated channels, is proved to be a crucial component to guarantee the favourable performance of the hypersonic precooled combined cycle engine. The system can sharply reduce the fuel consumption and cycle compressor pressure ratio (over 34% reduction in fuel consumption and over 45% reduction in cycle compressor pressure ratio, compared with ordinary single-route flow path design). The system is theoretically and quantitatively analysed. Operation mechanism, parameters design, feasibility and installing effects of the system are discussed. A performance simulation model is built for the paralleled system. The equivalent component method is proposed for measuring its effect on the engine overall performance. Inside the system, higher compression efficiency, lower pressure loss, more branches, higher heat transfer capacity and heat exchanger effectiveness can enhance the performance, while the feasible region, weight and size effects, and technical risks cannot be ignored either. For the engine, the installation of the paralleled system remarkably improves the engine performance and simplifies the compressor design. The paralleled system, with its advantage of coolant flow and compression work reduction, also can be beneficial to other applications in energy and power field.

1. Introduction

Next generation supersonic/hypersonic civil transportation has been growing as a highlighted topic in aviation science and industry [1]. Civil aviation, mostly powered by the fossil fuel, contributes 2.6% for CO_2 of total anthropogenic emissions now, and the CO_2 emission from aircrafts increases 3–4% per year due to the rapid growth of air transport [2,3]. In China, the rapid growth of aviation market and industry has also raised the concerns about CO_2 emission, and impelled the government to set an ambitious goal of over 60% CO_2 emission reduction around 2030 compared with the 2005 level. Research shows that fuel characteristics intensely influence the total CO_2 emission level, and targeted industrial policy (such as the encouragement for alternative fuel development) is needed to guarantee the pollution reduction goal [4]. Hydrogen is an ideal alternative energy source that has high heat of combustion, potentially generates zero emission and exists abundantly on earth [2]. Advantages such as longer range, larger payload and essentially less pollution have been revealed form years of research on hydrogen powered aircraft [5]. Facilities for liquid hydrogen production with different methods and technologies have been researched for more than a century, and the concept of holistic hydrogen supply chain has been recently proposed for measuring the

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https://doi.org/10.1016/j.apenergy.2018.03.062
Received 8 January 2018; Received in revised form 9 March 2018; Accepted 23 March 2018
Available online 27 March 2018

Nomenclature		θ,ψ	mapping relations
		A	heat transfer surface
n	Branch number	τ	time
T	total temperature	R	gas constant
P	total pressure		
l	specific compression work	*Subscript*	
h	total enthalpy		
Hex	heat transfer amount	i, j	tag of branch
π	pressure ratio	s	for single-route structure
η	adiabatic efficiency	in	compressor inlet section
k	adiabatic exponent	out	compressor outlet section
σ	total pressure recover coefficient of heat exchangers	I	system inlet section
$\dot{m}$	flow rate	O	system outlet section
δT	temperature gap in counterflow heat exchangers	min	minimum value
ε	heat exchanger effectiveness	*equiv.*	for equivalent components
C_P	specific heat		
α	coefficient of heat transfer amount	*Superscript*	
β	coefficient of compression work		
γ	coefficient of heat transfer	i	isentropic condition

economic and environmental effects of hydrogen infrastructure including liquefaction, transportation, and storage [6,7]. Recently developed large-scale hydrogen production is capable of provide enough cryogenic fuel for a considerable number of hydrogen powered vehicles [6]. The vision of eliminating the aviation pollution is raised up by applying hydrogen as alternative fuel.

The co-funded EC project LAPCAT, including the followed-up stages of LAPCAT I and II, has sketched a vision of civil hypersonic cruisers with flight Mach numbers of 5 and 8 [8]. The revolutionary precooled Scimitar engine is proposed for the Mach 5 cruiser. Rocket/DMR, advanced TBCC, and an integrated propulsion system (including modified GE90 turbofans, a liquid rocket and a dual-mode ramjet) are surveyed for the Mach 8 cruiser [8–11]. It can be revealed that advanced propulsion system with the capability of covering wide speed range is one of the most crucial issues of next generation high speed aviation, and that precooled engine is a feasible propulsion options [8,12,13].

Motivated by both performance and environment concerns, hydrogen powered precooled engine can be a suitable answer for advanced, clean, and high speed aviation in the future. Precooled engines are based on the concepts of intake air precooling and energy management. By precooling the high temperature air flow that stagnated from high Mach number and utilizing the thermal energy of the stagnated air, precooled engine enables air compression and improves engine performance [13,14]. Hypersonic precooled combined cycle engine (HPCCE), represented by the Scimitar engine of Reaction Engines Ltd. (REL), which is listed in the European LAPCAT project, is an attractive type of precooled engine [8,13]. HPCCE, powered by cryogenic hydrogen, contains three subsystems, including opened air cycle, closed heat-exchange-medium Brayton cycle and propellant system. The operation mechanism of the HPCCE is briefly shown in Fig. 1. The engine works as a precooled turbocharged ram/scramjet under hypersonic cruise conditions. While under subsonic cruise conditions, a bypass with a fan is added, which makes the engine work as a mix exhaust turbofan in a macroscopic view [13,14].

Advanced compact heat exchangers are crucial components of HPCCE, mainly including precooler (the heat exchanger between air and heat-exchange-medium), high temperature heat exchanger (the heat exchanger between the high temperature gas generated by preburner and heat-exchange-medium), and the heat exchangers working inside the closed Brayton cycle. Firstly, for precooler, the U.K., Belgium, and Spain researchers has focused on design and manufacture of heat exchangers such as Shell-and-Tubes and Plate-and-Fins, in which the performance of heat transfer and leak tightness is studied [15,16]. Experimental study on counterflow heat exchangers with small bore thin tubes has been done by the REL, for precooled engines including Scimitar and SABRE [17,18]. Beihang University also have investigated the design and manufacture of micro-size tube heat exchangers for precooled engines and intake air precooling technology [19]. A test bench for analysing the performance of the advanced compact heat exchanger is recently established, including a high temperature air wind tunnel, the coolant loop and data acquisition and testing system, as shown in Fig. 2. Preliminary performance test for a newly designed

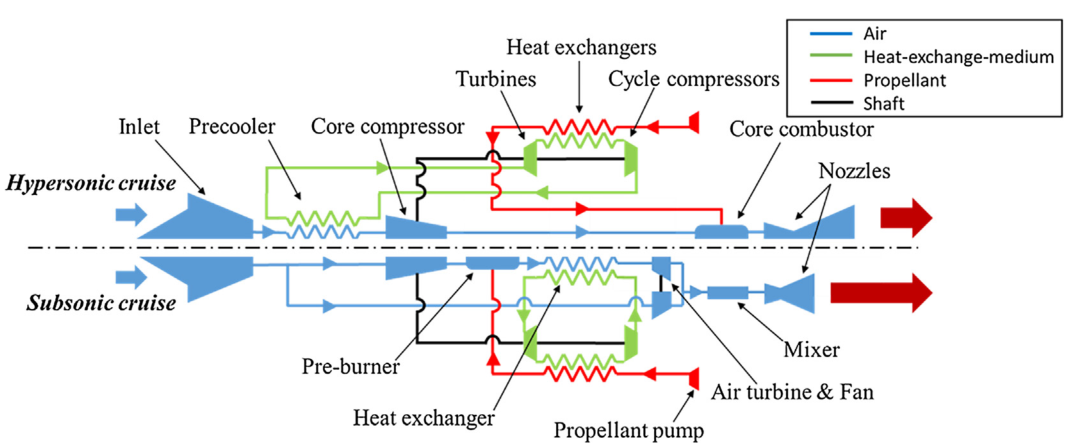

Fig. 1. The operation mechanism and basic structure of HPCCE [13].