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Thermodynamic efficiency analysis and cycle optimization of deeply precooled combined cycle engine in the air-breathing mode

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ABSTRACT

The efficiency calculation and cycle optimization were carried out for the Synergistic Air-Breathing Rocket Engine (SABRE) with deeply precooled combined cycle. A component-level model was developed for the engine, and exergy efficiency analysis based on the model was carried out. The methods to improve cycle efficiency have been proposed. The results indicate cycle efficiency of SABRE is between 29.7% and 41.7% along the flight trajectory, and most of the wasted exergy is occupied by the unburned hydrogen in exit gas. Exergy loss exists in each engine component, and the sum losses of main combustion chamber(CC), pre-burner(PB), precooler(PC) and 3# heat exchanger(HX3) are greater than 71.3% of the total loss. Equivalence ratio is the main influencing factor of cycle, and it can be regulated by adjusting parameters of helium loop. Increase the maximum helium outlet temperature of PC by 50 K, the total assumption of hydrogen will be saved by 4.8%, and the cycle efficiency is advanced by 3% averagely in the trajectory. Helium recirculation scheme introduces a helium recirculation loop to increase local helium flow rate of PC. It turns out the total assumption of hydrogen will be saved by 9%, that's about 1740 kg, and the cycle efficiency is advanced by 5.6% averagely.

1. Introduction

Air-breathing combined cycle engines have been rapidly developed to enable the reusable vehicles [1]. With the implementation of inlet-air cooling, the operation range of the air-breathing mode engine could be extended to Mach 6 with increased specific impulse [2]. Synergistic Air-Breathing Rocket Engine (SABRE) is a revolutionary deeply precooled combined cycle engine, characterized by both a great thrust as rocket engine and a high specific impulse as aircraft engine [1–3]. SABRE can be operated on dual-modes. In the air-breathing mode, it works like a turbojet engine with the air as the oxidant; when the aircraft reaches an altitude of 26 km with speed of Mach 5, it changes into rocket engine mode and climbs out of the atmosphere rapidly. The engine was first proposed by Reaction Engine Ltd. (REL) in 1989 as propulsion system the SKYLON project, which is designed to be a single-stage-to-orbit reusable spaceplane [3–5].

SABRE have attracted wide attentions [6–11] and big progresses on the key technologies have been obtained by REL [12–16]. For example, the ground experiment of PC has succeeded in 2012, and the company has thrown daylight on the plan of 1/4 scaling demonstration engine. The engine appears promising. However, there is scarce practical knowledge about the engine to the public. Some of the literature emphasize on the engine concept only [8,10,17], and few quantitative calculations are reported [18–20]. Víctor and Guillermo [18,19] developed a model for a high speed propulsion system with EcosimPro and the European Space Propulsion Simulation System. A full simulation has been done to compute the performance of SABRE during its air-breathing trajectory and the variation of thrust and specific impulse was yielded [18]. They also focused on the scimitar engine, which derived from SABRE and made some change with the cycle to fulfill different mission. A dynamic numerical model was developed for the engine along a determined trajectory between Mach 2.5 and 5. The thrust and specific impulse were detailed [19]. Moreover, the cycle efficiency has been evaluated according to the exergy analysis [21].

In generally, there are no much performance calculations of SABRE, especially on the cycle analysis, which is helpful for understanding of the engine. The operation characteristics of engine can be obtained by the cycle analysis, including the variation of cycle parameters, cycle efficiency and loss distribution. After all, the cycle analysis is necessary for both assessment and optimization of the engine. Exergy analysis is an important method for cycle analysis of engine, and it has been used widely for the aircraft engine, rocket engine and scramjet [21–29].

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Nomenclature

Abbreviation

AC	air compressor
BB	bypass burner
CC	main combustion chamber
CE	core engine
HeC	helium circulator
HeT	helium turbine
HeV	helium valve
HT1	hydrogen turbine1
HT2	hydrogen turbine2
HT3	hydrogen turbine3
HV	hydrogen valve
HX1	1# heat exchanger
HX2	2# heat exchanger
HX3	3# heat exchanger
HX4	4# heat exchanger
HX5	5# heat exchanger
LHP	liquid hydrogen pump
LHT	liquid hydrogen tank
PB	pre-burner
PC	pre-cooler
PRV	pressure reduction valve
RC	recirculator
REL	Reaction Engine Ltd
SABRE	Synergistic Air-Breathing Rocket Engine

Variables

A	area
C_m	coupling coefficient of conversion mass flow rate
C_π	coupling coefficient of pressure ratio
C_η	coupling coefficient of efficiency
Cp	specific heat at constant pressure
Ex	exergy
Ex_c	chemistry exergy
Ex_e	effective exergy
Ex_k	kinetic exergy
Ex_p	potential exergy
Ex_{ph}	physical exergy
Ex_q	heat exergy
F	thrust
h	specific enthalpy
Is	specific impulse
k	specific heat ratio
M	mass
$\dot{m}$	mass flow rate
n	rotating speed
P	pressure
Q	heat transfer rate
T	temperature
v	velocity
W	work
η	efficiency
π	pressure ratio
ρ	density
ΔEx	exergy loss
ΔP	pressure difference
ΔT	temperature difference

Subscripts

amb	ambient
c	compressor
e	exit
in	inlet
max	maximum
out	outlet
p	turbopump
sep	separate point
t	turbine

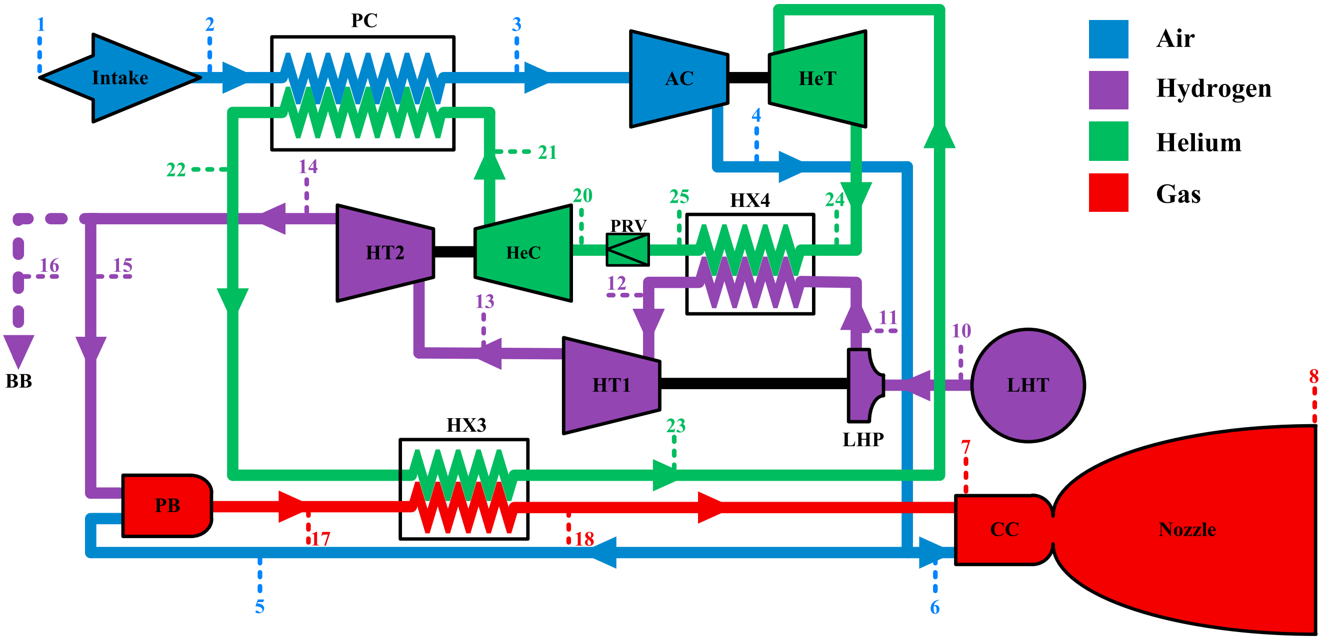

Fig. 1. Thermodynamic cycle schematic of SABRE in air-breathing mode.