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Review

Overview of the key technologies of combined cycle engine precooling systems and the advanced applications of micro-channel heat transfer

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ABSTRACT

A review of the key technologies of air-breathing engine precooling system and the use of micro-channel heat transfer is presented. A survey on various types of air-breathing engine cycles is presented, highlighting the characteristics of the energy cycles and the corresponding key technologies. The existing precooling schemes are classified into four types, *i.e.* Fuel Precooling (FPC), Mass Injection and Precompressor Cooling (MIPCC), combination of FPC and MIPCC, and Third-Fluid Cooling (TFC). Precoolers with micro-channel structures are found to have high heat dissipation capacity and high compactness. In detail, the applications of microchannel flow heat transfer like in the SABRE engine of the British Skylon spaceplane were introduced. Fundamental investigations on the microchannel heat transfer enhancement are essential for the development of the precooling technique. In order to better understand the micro-channel heat transfer mechanisms, experimental studies on single phase gaseous flow heat transfer in small flow passages are briefly overviewed, revealing some controversial conclusions on microscale flow and heat transfer characteristics. The limited experimental data on microchannel gaseous flow heat transfer largely hinders the theoretical development. Since the air precooling technique is at its infancy in China, experimental investigations are essential to overcome the gap.

1. Introduction

Hypersonic air-breathing combined cycle engines are rapidly developed to enable the reusable vehicles for SSTO (Single-Stage-to-Orbit) and TSTO (Two-Stage-to-Orbit). In air-breathing propulsion systems, the incoming flow needs to be effectively cooled before being compressed in the turbines in order to achieve high thrust-to-weight ratio, high specific impulse and improved engine performance. However, heat management in the air precooling systems is confronting rising challenges due to the extremely high heat dissipation capacity requirement in hyper-rocket speeding and intensified processes.

Efforts have been made for heat transfer enhancement. Micro- and mini-scale flow passages for the coolant in air-precoolers have been concentrated on thanks to their compact configuration and high heat removal potential. However, even though microchannel heat transfer has been utilized in some vehicles (*e.g.* Skylon spaceplane and its SABRE [43,45]), the drastically increasing heat transfer requirements of the aerospace vehicles are still calling for extensive investigations on the heat transfer mechanisms.

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The present study firstly surveys several representative air-breathing combined cycle engines and the corresponding precooling systems. The existing engine cycles were classified into four major types according to the precooling schemes. Representative engine cycles of each precooling scheme were introduced. Because of the request of heat exchangers with high heat dissipation capacity, the novel use of mini- and micro-channels was emphasized. Then, an example of the application of microchannel heat transfer in air-breathing engine precooling systems is introduced in detail, revealing the appealing prospect of microchannel heat transfer enhancement in air precooling systems. Subsequently, a brief summary of the experimental investigations on microchannel gaseous flow heat transfer is presented. Many questions in the controversial flow and heat transfer characteristics still need to be answered. Future research interests on microchannel flow and heat transfer are suggested, aiming at the development of the air-breathing precooling systems.

2. Representative precooling schemes in combined cycle engines

Combined cycle engines work by switching between the air-breathing mode (including turbojet/turbofan and ramjet) and the rocket mode for performance optimization during the flying. In the

Nomenclature

ACES	Air Collection and Enrichment System	MIPCC	Mass Injection and Precompressor Cooling
ATRDC	Deeply cooled air turborocket engine	SABRE	Synergetic Air-Breathing Rocket Engine
ATREX	Expander cycle Air Turbo Ramjet Engine	SSTO	Single-Stage-to-Orbit
FPC	Fuel Precooling	TFC	Third-Fluid Cooling
LACE	Liquid Air Cycle Engine	TLC	Thermochromic Liquid Crystal
LO_X	Liquid Oxygen	TSTO	Two-Stage-to-Orbit

Table 1
Summary of the combined cycle engines based on the precooling schemes.

Classification based on precooling scheme	Characteristics (pros/cons)	Key technologies
FPC		
LACE	Reduced mass and intensified structure by using the same nozzle for air-breathing and rocket modes; fuel consumption is very high with a relatively low specific impulse.	Icing problem. Air precooler design.
ACES	Liquid air separation after liquefaction, thus the liquid oxygen tank is empty when the vehicle takes off; liquefaction of the airstream increases the fuel consumption and the system complexity.	Air separator: O_2, N_2. Air precooler design.
ATRDC	A higher fuel/air ratio and an increased specific impulse; reduced system complexity; liquid hydrogen serves as the coolant in the precooler, which has potential safety threat.	Air precooler design.
MIPCC	Evaporative liquid increases the mass flow of the engine and increases additional thrust; cooling capacity is limited by simply injecting the volatile liquids into the hot air.	Selection of oxidizer. Injection system.
FRC&MIPCC		
KLIN	Simple configuration; light weight structure; high engine thrust to weight ratio; two–three times higher specific impulse than for LRE; known solution for icing problem.	Deep cooling without liquefaction; Icing problem: oxygen injection system.
ATREX	Increase the thrust and specific impulse in subsonic state.	Air precooler design Icing problem: injection system.
Third-fluid cooling		
SABRE	High heat dissipation capacity, compact structure; raise challenges in manufacture, material, and defrosting technique.	Icing problem. Manufacturing technique.

air-breathing mode, cooling the inlet airstream could help extend the flight range and improve the engine performance by increasing the thrust and specific impulse. There are several representative precooled combined cycle engines. Reviews on different engine cycles can be found in the open literature. However, there are few reviews based on the precooling schemes. The present survey classified the precooling schemes into four types, including Fuel Precooling (FPC), Mass Injection and Precompressor Cooling (MIPCC), combination of FPC and MIPCC, and Third-Fluid Cooling (TFC). Representative engine cycles of each precooling scheme such as LACE/ACE, ATRDC, MIPCC, KLIN, ATREX, and SABRE are summarized. The corresponding characteristics and key technologies are outlined in Table 1.

2.1. Fuel Precooling (FPC)

LACE

Liquid Air Cycle Engines (LACE) is developed from an LH_2/LO_2 rocket engine by introducing the air-breathing mode. The engine can operate from sea level static condition to Mach 6–7 [44]. The engine utilizes liquid hydrogen to liquefy the captured airstream. Then liquid air is pumped to a conventional rocket combustion chamber and serves as the oxidant for the combustion. In the rocket mode, the liquid air is replaced by liquid oxygen. The cycle of LACE is shown in Fig. 1. Only one nozzle is used for both operation modes of LACE, which largely reduces the mass and system compactness.

However, due to the process of air liquefaction, the fuel consumption of LACE is very high. Although the thrust/weight ratio and the Mach number range are satisfying, the LACE engine scarcely shows any outstanding performance due to its low specific impulse.

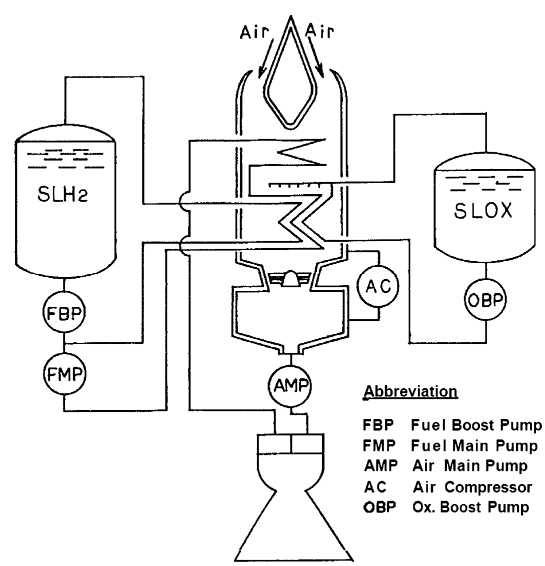

Fig. 1. LACE cycle for SSTO, Togawa et al. [41].

ACES

Air Collection and Enrichment System (ACES) was developed from LACE by adding an air separator, see Fig. 2 [14,44]. Similarly, the airstream is liquefied during air-breathing mode. Different from LACE, liquid oxygen and liquid nitrogen are separated after the air liquefaction in ACES. The liquid oxygen tank is empty when the vehicle takes off. After separation, the liquid oxygen is fed into the ramjet combustor and the residual liquid oxygen is stored for use in the rocket mode. At the same time, the liquid nitrogen serves