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Key parameters effects and design on performances of hydrogen/helium heat exchanger for SABRE

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ABSTRACT

Hydrogen/helium heat exchanger is a kind of heat exchanger dedicated to SABRE (Synergetic Air-breathing and Rocket Engine). Its special working environment and operating condition have brought a great challenge to its design. Hydrogen/helium heat exchanger with micro-channel/plate heat exchanger as its configuration is taken as the research object in this paper. Mathematical model of the heat exchanger is set up based on logarithmic mean temperature difference method, and the parameters that affect the heat transfer performance of heat exchanger is analyzed. The results showed that, reducing the thickness of fin or plate can help reduce the pressure loss of working fluids, the length and weight of hydrogen/helium heat exchanger. Reducing the width of micro-channel can reduce the length of heat exchanger and increase the height of heat exchanger. Reducing the height of micro-channel can reduce the length and height of heat exchanger. As a whole, the pressure loss of working fluids shows a trend of decreasing at first and then rising with the height or width of micro-channel rising. The pressure loss of helium is much greater than that of hydrogen, which means the pressure loss of helium is more sensitive to geometric parameters of heat exchanger and should be well controlled. In order to gain the best performance of the heat exchanger, the geometric parameters of heat exchanger is designed by Artificial Fish Swarm Algorithm.

Introduction

As the heart of airplane, the aero engine with good performance plays a key role in wide operating conditions. However, the limitation of the performance of a single kind of engine can't meet the needs of the aircraft such as hypersonic reconnaissance, penetration, long-range rapid strike and so on. As a result, the research and development plan of different types of combined cycle engines has been carried out in many countries, such as ATREX (Air Turbo Ramjet engine with Expander cycle), SABRE (Synergetic Air-breathing and Rocket Engine) and LACE (A liquefied air cycle engine) and so on [1–3], and the SABRE engine has received the most attention. In the research process, it encountered many technical difficulties such as design and manufacture technology of heat exchanger, matching technology of engine system parameters, suppressing frosting technology of pre-cooler, etc. Design technology of heat exchanger is one of the key technologies. Hydrogen/helium heat exchanger is dedicated to SABRE, and it is very important to analyze the performances of hydrogen/helium heat exchange for.

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Nomenclature

A	area of heat exchanger, m^2
C	heat capacity, kJ/K
c_p	specific heat capacity, kJ/(kg·K)
D_h	hydraulic diameter, m $W/m^2\cdot K$
H	height of heat exchanger, mm
h	height of micro channel, mm
k	convective heat transfer coefficient, $kW/(m^2\cdot K)$
L	length of heat exchanger, mm
m	mass flow rate, kg/s
Nu	Nusselt number
P	pressure of medium, MPa
Pr	Prandle number
Q	heat flux, kW
Re	Reynolds number
T	temperature, K
ΔT	temperature difference, K
t_f	thickness of fin, mm
t_p	thickness of plate, mm
U	heat transfer coefficient, $kW/(m^2\cdot K)$
v	velocity, m/s
W	width of heat exchanger, mm
w	width of micro channel, mm
γ	kinematic viscosity, m^2/s
λ	thermal conductivity, kW/(m·K)
η	total fin efficiency

Subscripts

0	plate between each layer of channels
1	Helium
2	Hydrogen
ave	average
i	inlet
max	bigger value
min	smaller value
o	outlet

SABRE engine is a hotpot currently and is proposed by Reaction Engines Ltd. Then a series of studies on SABRE and its components have been carried out [4]. Helium is adopted as a third working fluid to introduce a helium closed Brayton cycle into SABRE besides fuel and air. Hydrogen/helium heat exchanger is dedicated to SABRE and used to maintain power balance for thermodynamic system. The maximum temperature of medium of hydrogen/helium heat exchanger can reach 600–800 K and the minimum temperature is only 30–80 K, which causes a great temperature difference [5].

Reaction Engines Ltd intends to use PCHE (Compact Plate/Channel Heat Exchangers) as a hydrogen/helium heat exchanger configuration. The micro channel plate heat exchanger with aluminum material has been tested to verify its feasibility. At present, the use of high temperature alloy materials such as Inconel and Titanium Alloys for heat exchanger is under development [4]. Other research about hydrogen/helium heat exchanger we can search now is about using helium to cool hydrogen in CSNS (Spallation Neutron Source Project in China). Researchers from Zhejiang University took the hydrogen/helium heat exchanger as the research object, which is used in CSNS to cool supercritical hydrogen to 20 K by helium refrigeration cycle. The distribution of pressure, temperature and heat transfer coefficient are analyzed by MUSE software. The results showed that, the pressure dropping and the heat transfer coefficient of helium are the technical bottlenecks to improve the performances of hydrogen/helium heat exchanger [6]. In addition, there is a lot of research on micro channel heat exchangers for aero engines. For example, Refs. [7,8] have studied the thermal behavior in the cracking reaction zone of regenerative cooled scramjet cooling channels at different aspect ratios. The results indicate that increasing the channel aspect ratio will increase the pressure drop, but be not always beneficial for reducing the wall temperature because of thermal stratification.

In this paper, the heat transfer of hydrogen and helium occurs in micro-channel. So the analysis of heat transfer in micro channel is very important. So far, there has been a lot of research on micro-channel heat transfer performance. It is considered that the heat transfer coefficient of rectangular cross section micro-channel is highest at the same hydraulic diameter, comparing with trapezoidal cross micro-channel's and triangular cross section micro-channel's in the literature [9,10]. Choi et al. [11] have studied the heat transfer characteristic of N2 in a micro channel with circular cross section. The experiment results show that Nu is proportional to $Re^{1.7}$ in laminar flow and doesn't depend on Re in turbulent flow. Bucci [12] has found that Nu measured in experiments increases with the increment of Re and is higher than the value of Nu calculated by Hausen correlation in laminar flow. Todd et al. [13] have researched the forced convective heat transfer in single micro channel and multi-micro channels with rectangular cross section, using deionized water as working fluid. The results show that local Nu agrees with the traditional fully developed flow theory in pipe with Re ranging from 173 to 12900. Acosta et al. [14] investigated the teat transfer characteristic in micro channel with rectangular cross section whose hydraulic diameter is between 0.38 mm and 0.96 mm. The correlation agrees with that of a slightly larger pipe, and the surface roughness has a great influence on the heat transfer coefficient.

However, at present, most of the published literature are the researches about the development of SABRE or manufacturing technologies of the heat exchangers used in SABRE, and little is about the analysis of the performance of helium/hydrogen heat exchanger. What's more, there is only a little research on hydrogen/helium heat exchanger used in other fields. Though there are pretty many researches about the heat transfer performance and pressure loss of hydrogen or helium in a channel. In practical application, the performance is limited by space and the ability to supply pressure, which differs from the analysis and experiment using a single channel. It is limited for us to understand hydrogen/helium heat exchanger well, but also unfavorable for us to understand and optimize the advanced propulsion systems. As a result, the hydrogen/helium heat exchanger is taken as the research object in this paper. The micro-channel/plate heat exchanger is chosen as its configuration. Mathematical model of the hydrogen/helium heat exchanger is established by MATLAB. The thickness of fin and plate and the width and