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Effects of Air Vitiation on Scramjet Performance Based on Thermodynamic Cycle Analysis

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Abstract

The influences of air vitiation on scramjet performance were studied in this paper based on thermodynamic cycle analysis. By the aid of NASA Glenn's computer program Chemical Equilibrium with Applications (CEA), parameters of vitiated air at combustion heater exit could be calculated. Based on thermodynamic cycle analysis, scramjet performance, including internal thrust, specific thrust, and specific impulse, were analyzed with 9 simulation criterions under Mach 4.5 and 6.5 conditions, respectively. The results show that, (1) specific heat and specific heat ratio of vitiated air are mainly affected by combustion heating medium, and also have minor connection with temperature criterions. Moreover, choosing different simulation criterions influences the temperature or pressure between clean air and vitiated air significantly; (2) the internal thrust and specific thrust of scramjet with hydrogen heated airstream are greater than that of scramjet with alcohol and kerosene heated airstream; (3) matching static pressure and dynamic pressure will obtain higher internal thrust compared to total pressure, and the effect of pressure criterions on internal thrust is more remarkable than temperature criterions. On the other hand, these findings proved that the method based on thermodynamic cycle analysis is a simple, dependable, and effective approach to evaluate the scramjet performance affected by air vitiation.

Keywords: Air vitiation; Scramjet; Performance; Thermodynamic cycle

Introduction

A large number of researches have been made to develop the hypersonic airbreathing propulsion systems (especially scramjet). One of effective research methods is conducting meaningful ground tests. With the information gained from experimental tests, Computational Fluid Dynamics (CFD) simulation can not only describe the details of complex flow field accurately, but also expand flight envelop which is not achievable at ground tests. In addition, theoretical analysis provides a quick and reliable approach to assess scramjet. Based on above three methods, lots of critical techniques and problems, such as combustion oscillations in supersonic combustor, combustion mode analysis, re-cooled cycle and thermal management system of hydrogen-fueled scramjet, were investigated in recent years [1-4]. Inevitably, the research of scramjet will be more and more intensive and extensive in the future.

In order to simulate the real flight conditions at ground tests, generating high-enthalpy flow is necessary. For example, the stagnation temperature of engine airstream is about 1100 K at Mach 4.5 and the corresponding stagnation enthalpy reach over 1 MJ/kg. The methods of air heating are currently as follows [5]: combustion heating, shock tube heating, arc heating, storage heating, and electric heating. Because of the ease of operation, the low operating cost and the supply of long test times, combustion heating has become the most widely used method of producing high-enthalpy air.

The main disadvantage of combustion heating is the introduction of contaminating species, which primarily include H_2O and CO_2, and little other radical species, such as OH, O, H and NO. As a result, the vitiation contaminates lead to differences of physical property and flow parameter between clean air and combustion-heated (vitiated) air. For instance, when hydrogen is used to heating air, the mole fraction of H_2O in vitiated air could reach 12% at 1200 K total temperature simulation, which changes the specific heat of vitiated air to 1280 $Jkg^{-1}K^{-1}$ [6]. When selecting hydrocarbon fuel to combust air, the contaminating species will contain not only water but also carbon dioxide. Changing the thermodynamic properties of engine inflow through vitiation has been shown to lower both the combustion-induced temperature rise and the internal thrust in a scramjet engine [7]. Extrapolating vitiated air measurements directly to flight could result in over fueling of the combustor and possible inlet unstart [8,9].

Previous studies related to vitiation effects focus mainly on pressure and temperature variation in supersonic combustor, mode transition of dual-mode scramjet, and ignition and flame holding of scramjet, etc. It was discovered that as the increase of the level of H_2O, CO_2 or H_2O and CO_2 in vitiated air, the pressure rise due to combustion and isolator shock train length decreased and the combustion mode might be changed [10]. The fuel equivalence ratio at which mode transition takes place raised when compared with clean air [11,12], and the influence of water and carbon dioxide on combustor performance was nonlinear as the concentration of vitiation species increased [13]. Li Jianping et al. [14] made two-dimensional calculations of kerosene-fueled supersonic combustion, finding that the presence of vitiation components lead to combustor performance deterioration characterized by the decrease of temperature rise, combustion efficiency and stream wise impulse relative to those in clean air. The effects of vitiated air on ignition and flame holding were also studied broadly [15,16]. Pellet et al. [15] reviewed vitiation effects on scramjet ignition and flame holding, and

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revealed that the existence of H_2O may change the reaction kinetics. Generally, all of the above studies matched total pressure and total temperature between clean air and vitiated air, so matching other parameters, such as static pressure, total enthalpy, become another research focus [11,13,17]. It was revealed that matching total enthalpy rather than total temperature get closer mode transition critical equivalence ratio related to clean air [11].

However, ground test and numerical simulation cost too much and need a lot of time. It is necessary to evaluate the effects of different heating mediums and matching schemes on scramjet performance quickly and easily. To achieve this, a calculation method based on thermodynamic cycle analysis introduced was introduced. Via this method, the qualitative tendencies and rules of vitiation effects on scramjet performance are available, which supply effective guidance on the selection and validation of heating mediums and simulation criterions. More important, this method will save plenty of costs and time.

This paper assesses the impact of simulation criterions on vitiated air properties entirely and evaluates three combustion heaters by the help of well-developed chemical equilibrium applications and thermodynamic cycle analysis method. The results will be in favor of understanding the characteristics of vitiated air and its effects on scramjet performance. The article begins with calculation and analysis of parameters of vitiated air at combustion heater exit. Then, method based on thermodynamic cycle analysis is introduced, and the results will be represented in detail.

Parameters of Vitiated Air

This section gives an example of how to calculate the components of vitiated air at combustion heater exit, firstly. Then, parameters of vitiated air, including specific heat, specific heat ratio, static temperature, and static pressure are discussed amply. Meantime, comparison of Mach 4.5 and 6.5 conditions is also presented.

Method of calculating vitiated air parameters

Before estimating scramjet performance, the parameters of vitiated air at combustion-air preheater exit must be calculated. By mixing, burning fuel and air with ambient temperature, combustion heater supply engine with simulated total temperature inflow. Due to the introduction of heating fuel, the components of vitiated air will differ from clean air, resulting in the differences in specific heat, specific heat ratio, and so on. One method of acquiring the components of vitiated air is to make use of the NASA Glenn's computer program *Chemical Equilibrium with Applications* (CEA) [18].

Because of the differences of thermodynamic properties between clean air and vitiated air, matching part of their parameters will lead to the distinction of other parameters. For instance, it is impossible to match static temperature and total temperature or total enthalpy at the same time. Therefore, it is significant to estimate the effect of different simulation criterions on parameters of vitiated air and scramjet performance. Table 1 lists 9 simulation criterions, where T_t is total temperature, T_s is static temperature, H_t is total enthalpy, p_t is total pressure, p_s is static pressure, p_d is dynamic pressure, Ma is flight Mach number. Table 2 presents parameters of clean air as the standard conditions. In clean air, the mole fractions of N_2 and O_2 are 78% and 21%, respectively. Little CO_2, almost 0.03%, and other species also exist in clean air, but they are negligible. As for an example, the first simulation criterion, T_t - p_t - Ma was chose to show how the parameters of vitiated air are obtained. To ensure the consistence between clean air and vitiated air, the mole fraction of O_2 was fixed at 21%. Then, the Mach number, total temperature and total pressure of vitiated air were set with the same value of clean air. There are three fuels for heating air, that is, alcohol, hydrogen, and kerosene. After choosing one of the heating fuels, the compositions of vitiated air were gained by using CEA. This paper focuses only on two vitiation species, H_2O and CO_2.

Table 3 gives the mole fractions of H_2O and CO_2 in vitiated air at Mach 4.5 and 6.5, respectively, corresponding to T_t - p_t - Ma criterion. As shown in Table 3, hydrogen heater can only generate H_2O, but alcohol heater and kerosene heater will produce H_2O and CO_2, whose concentration are determined by the level of simulated total temperature. Using other programs, the specific heat C_p, specific heat ratio γ and other parameters might be obtained. Table 4 shows some calculated parameters of vitiated air at Mach 4.5 and 6.5.

Calculated results

Specific heat of clean air and vitiated air at Mach 4.5 and Mach 6.5 are shown in Figures 1 and 2, respectively. Because of containing

Criterions	Parameters
1	T_t-p_t-Ma
2	H_t-p_t-Ma
3	T_s-p_t-Ma
4	T_t-p_d-Ma
5	H_t-p_d-Ma
6	T_s-p_d-Ma
7	T_t-p_s-Ma
8	H_t-p_s-Ma
9	T_s-p_s-Ma

Table 1: Simulation criterions.

Ma	T_s, K	p_s, kPa	T_t, K	p_t, kPa
4.5	216.7	6.936	1049	2164
6.5	223.6	1.879	1901	6340

Table 2: Standard conditions of clean air at Mach 4.5 and Mach 6.5.

Heating fuel	O_2, %		H_2O, %		CO_2, %	
	Mach 4.5	Mach 6.5	Mach 4.5	Mach 6.5	Mach 4.5	Mach 6.5
Alcohol	21.00	21.00	6.25	16.72	4.20	11.22
Hydrogen	21.00	21.00	10.50	27.60	0.02	0.02
Kerosene	21.00	21.00	4.08	10.76	4.27	11.30

Table 3: Mole fractions of O_2 and vitiation species in vitiated air with criterion 1.

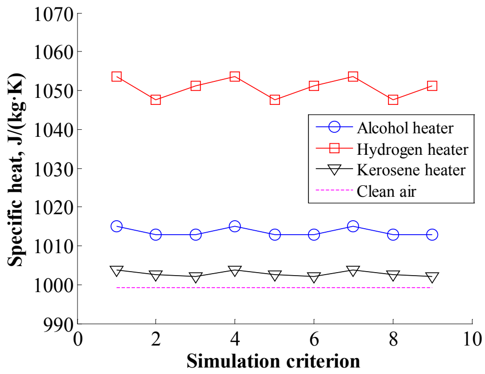

Figure 1: Specific heat of clean air and vitiated air at Mach 4.5.

Heating fuel	C_p, Jkg^{-1}K^{-1}		γ		T_s, K		p_s, Pa	
	Mach 4.5	Mach 6.5	Mach 4.5	Mach 6.5	Mach 4.5	Mach 6.5	Mach 4.5	Mach 6.5
Alcohol	1015.0	1048.8	1.388	1.370	224.54	251.03	6489.44	1250.92
Hydrogen	1053.7	1156.4	1.391	1.377	222.17	242.95	6659.03	1463.74
Kerosene	1003.7	1016.9	1.390	1.374	223.61	247.11	6535.46	1315.19

Table 4: Calculated parameters of vitiated air with criterion 1.

Conditions	Clean airstream	Alcohol heated airstream	Hydrogen heated airstream	Kerosene heated airstream
***Ma* 4.5**	0.65	0.58	0.60	0.58
***Ma* 6.5**	0.65	0.50	0.55	0.51

Table 5: Combustion efficiency at different conditions.

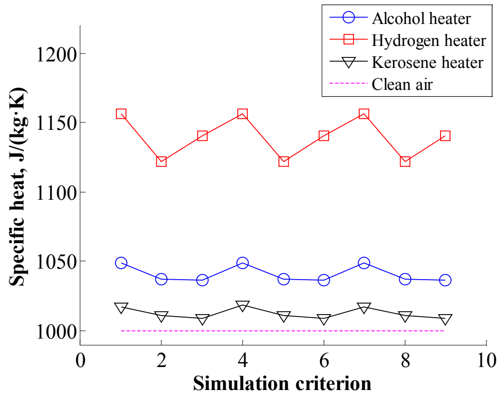

Figure 2: Specific heat of clean air and vitiated air at Mach 6.5.

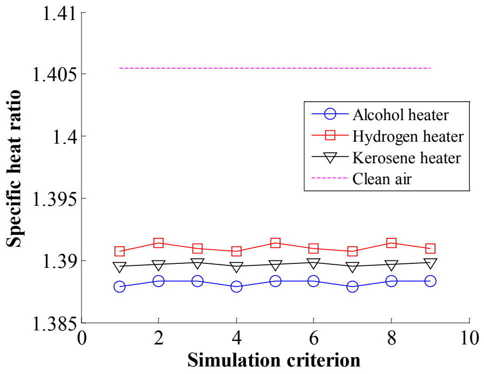

Figure 3: Specific heat ratio of clean air and vitiated air at Mach 4.5.

a certain amount of H_2O, whose specific heat is the largest among all components of air, the specific heat of vitiated air is greater than that of clean air, which is set at 1006 Jkg^{-1}K^{-1}, at all criterions. Furthermore, as the volume of water generated by hydrogen heater is bigger than others, the specific heat of vitiated air produced by hydrogen heater is the highest, as shown in (Figures 1 and 2), followed by alcohol heater, then kerosene heater. Evidently, because more water was brought into vitiated air at Mach 6.5, the corresponding specific heat of vitiated air is bigger than those at Mach 4.5 condition.

Figures 3 and 4 show specific heat ratio of clean air and vitiated air at Mach 4.5 and Mach 6.5, respectively. As we known, the specific heat ratio is determined by both mean molecular weight and specific heat of gas. The presence of H_2O will decrease mean molecular weight of vitiated air and increase specific heat of vitiated air. Inversely, CO_2 can enhance mean molecular weight and reduce specific heat of contaminated air. As a result, the specific heat ratio of vitiated air has minor distinction (± 0.01) between 3 combustion heaters. However, the specific heat ratios of vitiated air are smaller than that of clean air, as the specific heat ratios of H_2O and CO_2 are fewer than that of N_2.

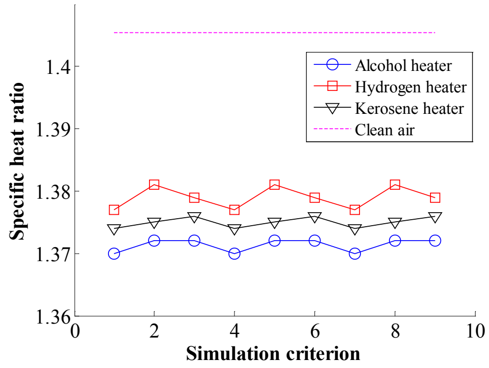

Figure 4: Specific heat ratio of clean air and vitiated air at Mach 6.5.

When different temperature criterions are matched for the same combustion heater, the volume of heating fuel varies, causing the disparities of concentration of H_2O and/or CO_2 in vitiated air. Generally, the difference in hydrogen heater is moderately obvious and selecting total temperature will produce more water. However, for alcohol or kerosene heater, volumes of H_2O and CO_2 have few distinctions at different criterions, leading to the approximate value of specific heat and specific heat ratio, as shown in Figures 1-4. What's more, no matter which pressure criterions are matched, the specific heat and specific heat ratio are just identical.

Static temperatures of vitiated air and clean air at Mach 4.5 and Mach 6.5 are shown in Figures 5 and 6, respectively. When simulating total temperature (criterion 1, 4 and 7), the static temperature is inversely proportional to specific heat ratio, causing that static temperatures of vitiated air are greater than that of clean air. While matching total enthalpy (criterion 2, 5 and 8), the static temperature is inversely proportional to both specific heat and specific heat ratio. The results with Mach 6.5 show the same trends.

Figures 7 and 8 show static pressure of vitiated air and clean air at Mach 4.5 and Mach 6.5, respectively. Static pressure is in proportion to γ when matching total pressure and in inverse proportion to γ when simulating dynamic pressure. As a result, the static pressure of vitiated air is smaller than that of clean air when matching total pressure and greater than that of clean air when simulating dynamic pressure.

It can be concluded from this section that the combustion products introduced to vitiated air have considerable effects on its properties. The specific heat of vitiated air is greater, but the specific heat ratio is

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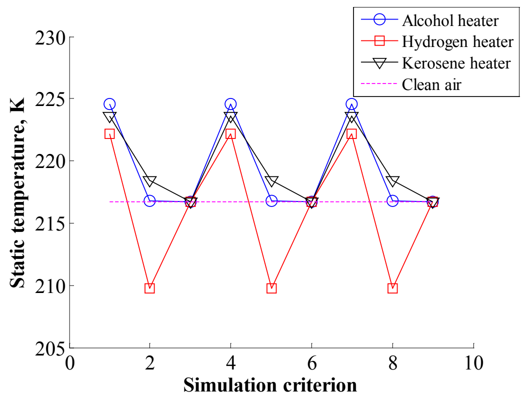

Figure 5: Static temperature of vitiated air and clean air at Mach 4.5.

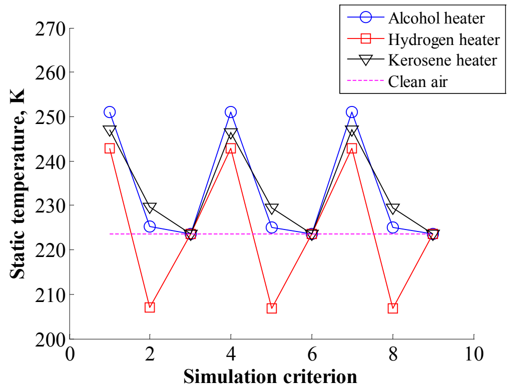

Figure 6: Static temperature of vitiated air and clean air at Mach 6.5.

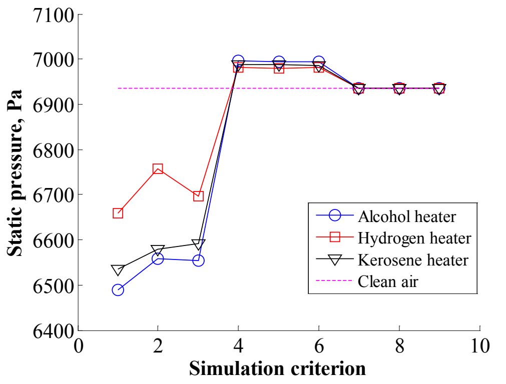

Figure 7: Static pressure of vitiated air and clean air at Mach 4.5.

smaller, than that of clean air. Specific heat and specific heat ratio of vitiated air are mainly determined by combustion heating medium, and there also are few distinctions for the same combustion heater when select different temperature criterions. Besides, simulation criterion affects the temperature and pressure between clean air and vitiated air significantly. What's more, the vitiation effects are more obvious at Mach 6.5 condition. With the parameters of vitiated airstream, the scramjet performance can be calculated at next.

Assessment of Scramjet Performance

Method of calculating scramjet performance

The method of estimating scramjet performance is based on the 4th chapter of [19], which deals with hypersonic airbreathing engine performance analysis. As described in [19], the real thermodynamic cycle of scramjet is composed of four process, 1) adiabatic compression, 2) constant pressure combustion, 3) adiabatic expansion, 4) constant pressure heat rejection. By means of thermodynamic closed cycle analysis and first law analysis, it is capable to find closed solutions for performance of real ramjets and scramjets and use them to expose important trends and sensitivities. Furthermore, stream thrust analysis can easily account for several phenomena that can have a significant influence on airbreathing engine performance, such as the mass, momentum, and kinetic energy fluxes contributed by the fuel, the geometry of the burner, and exhaust flows that are not matched to the ambient pressure [19]. The above methods provide sufficient detail and accuracy to assess the performance of scramjet. The formulas for calculating scramjet internal thrust, specific thrust, and specific impulse are as follows:

$$Fs=(1+f)S_{a9}-S_{a3}-\frac{R_3T_3}{c_3}(\frac{A_9}{A_3}-1)\;\backslash\text{* MERGEFORMAT} \tag{1}$$

$$F=Fs\cdot\dot{m}_a\;\backslash\text{* MERGEFORMAT} \tag{2}$$

$$Is=F/\dot{m}_f\;\backslash\text{* MERGEFORMAT} \tag{3}$$

where F_s is specific thrust of scramjet, F is internal thrust of scramjet, I_s means specific impulse of scramjet, f means fuel/air ratio, Sa is stream thrust function, reference station 3 corresponds to combustor entrance, reference station 9 corresponds to external expansion ends, R is the gas constant, T is static temperature, c is velocity, m_a means airstream mass flow rate, m_f means fuel mass flow rate. It should be noted that in the adiabatic compression process, the calculated airs parameters at inlet exit is inconsistent of the real shock wave compress process. However, if experiments were conducted at direct-connect facility, the process of compression can be omitted. On the other hand, with the help of numerical simulation, if necessary, the real air parameters at inlet exit (that is, combustor entrance) are obtainable.

As presented before, the main difference between vitiated air and clean air lies in their thermodynamic properties and flow parameters. In addition, the parameters of airstream vary along with the process of

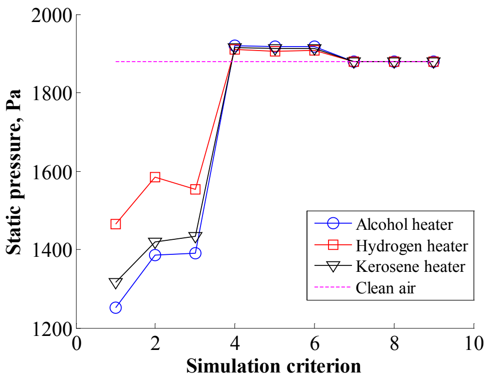

Figure 8: Static pressure of vitiated air and clean air at Mach 6.5.

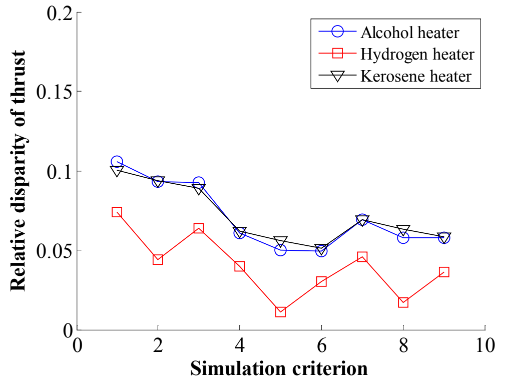

Figure 9: Relative difference of thrust between clean air and vitiated air inflow scramjet at Mach 4.5 (φ=1).

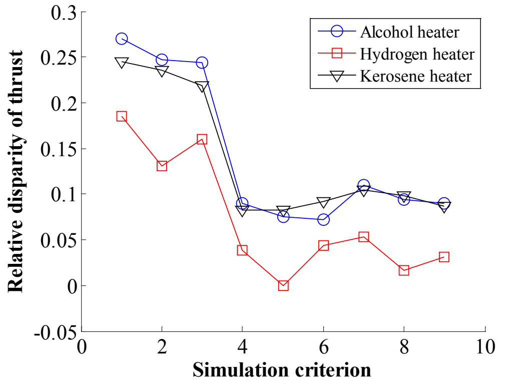

Figure 10: Relative difference of thrust between clean air and vitiated air inflow scramjet at Mach 6.5 (φ=0.6).

heat addition and expansion. Hence, the effects of parameter variation on engine performance must be taken into account. In this article, the heat addition process and expansion process were divided into a number of sub processes. At each sub process, the properties of flow were regarded as constant. In view of this, the approach can be used to evaluate scramjet performance related to air vitiation. Considered that H_2O and CO_2 have significant chemical kinetic effects on combustion process, the combustion efficiency of combustor must be taken into consideration. Referring to [9] and [20], the combustion efficiency of combustor with clean airstream and vitiated airstream are presented in Table 5. The fuel of scramjet is $C_{12}H_{23}$.

Calculated results

Figures 9-14 show relative disparities of thrust (all thrust means internal thrust at next), specific thrust and specific impulse between clean air inflow scramjet and vitiated air inflow scramjet at Mach 4.5 and 6.5 conditions, which have different fuel equivalence ratios φ. As shown in Figures 9 and 10, thrust corresponding to hydrogen heater is larger than others at the same criterion. Also, the thrust of vitiated airstream scramjet is smaller than that of clean airstream scramjet. As listed in Table 3, there are about 10% H_2O (mole fraction) in vitiated air produced by hydrogen heater and 6% H_2O+4% CO_2 in alcohol heater generated air at Mach 4.5. Hence, it proved that vitiation species decrease the thrust of scramjet and the effect of CO_2 on thrust is greater than H_2O. What's more, the effects become intenser at Mach 6.5 condition for more introduced vitiation species.

For the same heater, selecting static pressure or dynamic pressure as criterion can obtain larger thrust compared to total pressure, as shown in Figures 9 and 10. For alcohol heater or kerosene heater, matching static temperature get greater thrust. And for hydrogen heater, choosing total enthalpy will gain bigger thrust. As calculated above, when matching static temperature for alcohol and kerosene heater or total enthalpy for hydrogen heater, the total temperature of vitiated air is the lowest. In this case, therefore, the quantity of vitiation species is lower than other schemes. In summary, the influence of pressure criterions on thrust is stronger than temperature criterions and the effects will be enhanced with the increasing Mach number.

Because the specific thrust is mainly affected by mass fraction of oxygen in airstream, which is in proportion to fuel/air ratio *f*, the specific thrust of scramjet vitiated by hydrogen heater is greater than others, as shown in Figures 12 and 13. Clearly, the specific impulse with vitiated air inflow is less than that of clean air. It should be considered that the combustion efficiency of scramjet could be inconsistent at different simulation criterions. Therefore, the trends of specific impulse will also be affected by combustion efficiency, which is our main future work.

Compared with experimental and numerical results referred to [6-14], the essential tendency of vitiation effects on scramjet performance is identical, which evidenced that the method based on thermodynamic

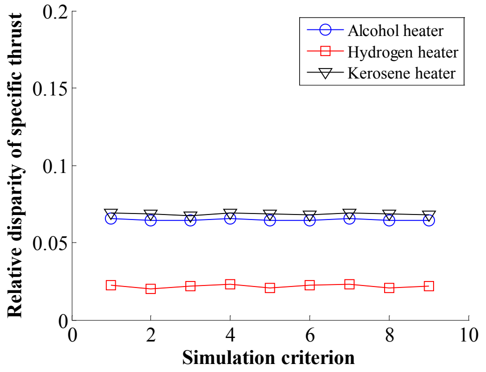

Figure 11: Relative difference of specific thrust between clean air and vitiated air inflow scramjet at Mach 4.5 (φ=1).

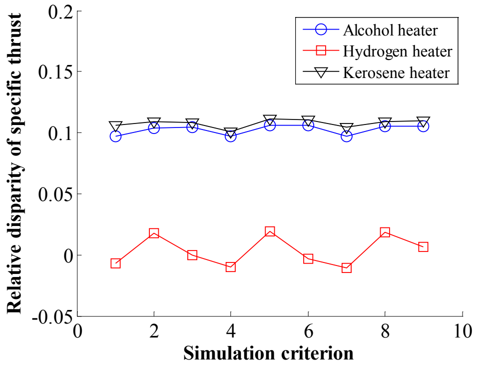

Figure 12: Relative difference of specific thrust between clean air and vitiated air inflow scramjet at Mach 6.5 (φ=0.6).

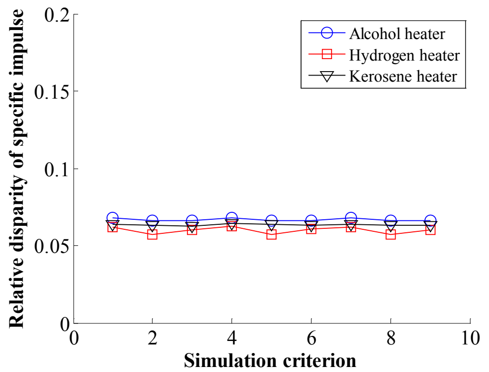

Figure 13: Relative difference of specific impulse between clean air and vitiated air inflow scramjet at Mach 4.5 (φ=1).

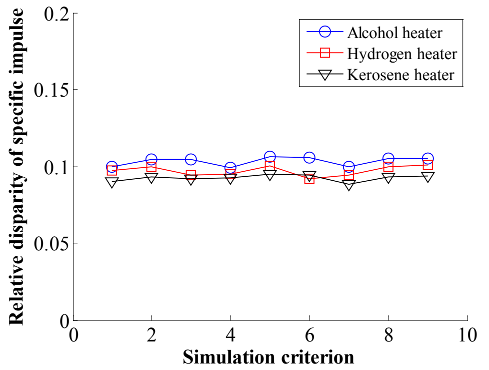

Figure 14: Relative difference of specific impulse between clean air and vitiated air inflow scramjet at Mach 6.5 (φ=0.6).

cycle analysis can validate and predict ground test results effectively and offer forecast when choosing simulation criterions and heating mediums. Therefore, this method will economize lots of costs and time. It should be noted that the theoretical calculations indeed cannot interpret all the authentic conditions in scramjet, it just provide a proper approach to predict the correct qualitative tendency. If we want to obtain the accurate quantitative effects, plenty of ground tests are inevitable.

Conclusions

The effects of contaminating species in vitiated air on scramjet were calculated by chemical equilibrium applications and theoretical analysis based on thermodynamic cycle with 9 simulation criterions. The method based on thermodynamic cycle analysis supply a quick, simple, and reliable approach to evaluate the scramjet performance related to vitiation effects. Properties of vitiated air heated by alcohol, hydrogen and kerosene combustion heater and scramjet performance (internal thrust, specific thrust, and specific impulse) were assessed at Mach 4.5 and 6.5 conditions, respectively, for the purpose of revealing the impact of combustion heating medium and finding out the optimum selection of simulation criterion. There are plenty of findings which can increase the understanding of vitiation effects on scramjet.

Specific heat and specific heat ratio of vitiated air are mainly determined by combustion heating medium, and also have minor connection with temperature criterions. The specific heat of vitiated air is greater, but specific heat ratio of vitiated air is smaller than that of clean air. Moreover, the specific heat of vitiated air produced by hydrogen heater is the largest, followed by alcohol heater, then kerosene heater. Simulation criterions have great effect on temperature and pressure of vitiated air. What's more, the above differences are more obvious at Mach 6.5 relative to Mach 4.5.

The thrust and specific thrust of scramjet vitiated by hydrogen heater are greater than that of alcohol heater and kerosene heater at Mach 4.5 and 6.5 conditions. In addition, the scramjet thrust and specific impulse with vitiated air inflow is less than that of clean air. The performance of vitiated scramjet declines with the increasing Mach number. Simulating static pressure and dynamic pressure can obtain greater thrust compared to total pressure. The influence of pressure criterions on thrust is more remarkable than temperature criterions.

As the combustion efficiency was estimated by the help of references, further study will focus on the effects of chemical kinetic on combustion. In general, this method can calculate scramjet performance with all kinds of fuel and other simulation criterions and Mach number. It will be a significant guidance related to air vitiation effects on scramjet performance.

Nomenclature

c	velocity, m/s
Cp	specific heat, kJ/(kg·K)
f	fuel/air ratio
F	internal thrust, N
Fs	specific thrust, N·s/kg
Ht	total enthalpy, J/kg
Is	specific impulse, N·s/kg
$\dot{m}_a$	air mass flow rate, kg/s
$\dot{m}_f$	fuel mass flow rate, kg/s
Ma	Mach number
pd	dynamic pressure, kPa
ps	static pressure, kPa
pt	total pressure, kPa
Sa	stream thrust function, m/s
Tt	total temperature, K
Ts	static temperature, K
γ	specific heat ratio
φ	fuel equivalence ratio

Subscripts`

a	air
d	dynamic
f	fuel
s	static
t	total

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