Investigation of Vitiated Species on the Effect of Scramjet Combustion Using Fuel of Hydrogen or Ethylene

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Received: March 20, 2012 Accepted: April 5, 2012 Online Published: May 1, 2012

doi:10.5539/mas.v6n5p73 URL: http://dx.doi.org/10.5539/mas.v6n5p73

Abstract

In ground test of the scramjet, the air is heated by burning oxygen in oxygen-enriched air to simulate the flight enthalpy. As result, test media are contaminated by species (H_2O, H, O, OH and CO_2), which are not of representative in the actual atmosphere. In the article, the high enthalpy air is simulated by used the resistance heater, meantime vitiated species is introduced to the high enthalpy air. The effect of combustion is investigated by the experiments used the fuel of hydrogen or ethylene, when the test media are contaminated by H_2O and CO_2. At the same time, the effect of scramjet combustion is researched by numerical simulated. The result: the effect on the wall pressure and the combustion performance is markedly when the coming flow with contamination of H_2O and CO_2.

Keywords: scramjet, contaminate, combustion, performance, enthalpy

I. Introduction

The high enthalpy gas with properties representative of those at flight conditions was simulated on the ground testing of scramjet. In general, the Mach number, temperature, pressure and species of parameters of flow were matched. The combustion heater was usually used to simulate the high enthalpy gas, with 21% mole percent of O_2 at the exit of heater. As result, there were different between high gas and really air of flight because of the vitiated species introduced.

It was difficult that the high enthalpy gas was supplied with no vitiated species on the testing of scramjet. In currently, the method of air heating: 1) electric heating, 2) combustion heater, 3) storage heater, 4) shock tube heating. In these methods of air heating, the test gas could be vitiated by some certain species, such as H_2O, H, O, OH, CO_2 and NO etc. The properties of test gas would be changed by these vitiated species, which had effect on the performance of combustor.

Rogers (1986) assessed the vitiation effects of NO and H_2O on the ignition and reaction of hydrogen. Three models of the burning process were simulated with detailed chemical kinetics. As result: the ignition was promoted by the ions of H, O, OH. He demonstrated the promotion effect of NO and the retardation effect of H_2O in the diffusion-controlled combustion.

Mitani T. et al. (1996) compared the free jet scramjet test with the fuel of hydrogen on the facility of RJTF with the heating methods of SAH or VAH. In the nozzle exit of heater, only specific heat among the all thermodynamic parameter was different. The result of test demonstrated: the ignition was promoted as VAH used, and the thrust of scramjet applied SAH was higher than VAH.

The resistive heating elements at University of Virginia was be used to investigate the effect of vitiated species of H_2O and CO_2 on the performance of scramjet combustor with fuel of hydrogen by McDaniel Jr. J. C. et al. (2003). To permit simulation of a combustion heated, high enthalpy facility required the addition of vitiated species and O_2 (to maintain a mole fraction 21%) to match contaminants present in a vitiated flow. At Mach number 2 of facility nozzle exit, unswept ramp injectors were in the combustor. H_2 was injected at Mach 1.7, normal to the ramp base. As researched results: (a) At a fixed fuel equivalence ratio of 0.27, 5% H_2O, and 5% H_2O plus 2.5% CO_2, the combustor pressure distribution decreased by 10% and 12% respectively. (b) For a fuel equivalence ratio of 0.35, the combustor operated in a dual mode with dry air, but in the supersonic mode when vitiated with 7% H_2O. An approximate Rayleigh calculation for this case predicts that 71% of the measured pressure decrease with vitiation was due to thermodynamics and 29% to chemical kinetics. The results of test of

University of Virginia demonstrated that directly extended the conclusion of vitiated air to the conditions of really flight would make to increase to the quantity of feed the fuel.

In broad, Liu ling investigated that the effect of H_2O on the ground test of supersonic combustion used the arc heating element. At Mach number 2.1, the vapor was injected nine times to simulate vitiated species, the mole fraction 1.2%, 2.7%, 3.7% of the coming flow, respectively, but no oxygen was supplemented into the flow. The results indicated: the effect of H_2O couldn't be ignored in certainly conditions.

In this article, the vitiated species was simulated to apply addition vitiated species to gas of nozzle exit of direct-connected resistance heated wind tunnel. The effect of vitiated species on the wall-pressure of supersonic combustor was investigated. Then CFD simulations of reacting flow field in the combustor were conducted to investigate the effect of vitiated species on the performance of supersonic combustor.

2. System of Test and Model

2.1 System of Test

The test was conducted by used the direct-connected resistance heater wind tunnel of Northwestern Polytechnical University. The power of resistance heater is 750 kw. In sure of security of direct-connected resistance heated wind tunnel, the max mass rate of coming flow wasn't lower 0.5 kg/s by limited. The exit total temperature of the resistance heater as main component of the facility can reach about 600~1000 K corresponding to air flow ratio of 1.5~0.73 kg. The facility character of the resistance heater was that clean high enthalpy may be obtained for scramjet test.

Investigated effect of vitiated species, the simply methods were to compare the results of vitiated air and clean air of test. The effect of vitiated species was simulated by addition species of H_2O and CO_2 into clean high enthalpy gas in mixture room, and replenishment oxygen into gas with uniformity density, temperature of flow parameter at exit of mixture room. In order to avoid addition species interfere upstream flow with a Venturitube in front of mixture room. When clean air was needed for clean air scramjet test, it was used that same the Venturitube and mixture room, only different from vitiated air test not any more H_2O, CO_2 and O_2 were additional. Therefore, all flow parameter were equal to compared vitiated air and clean air test, used same the facility nozzle, model combustor, and fuel/air equivalence ration.

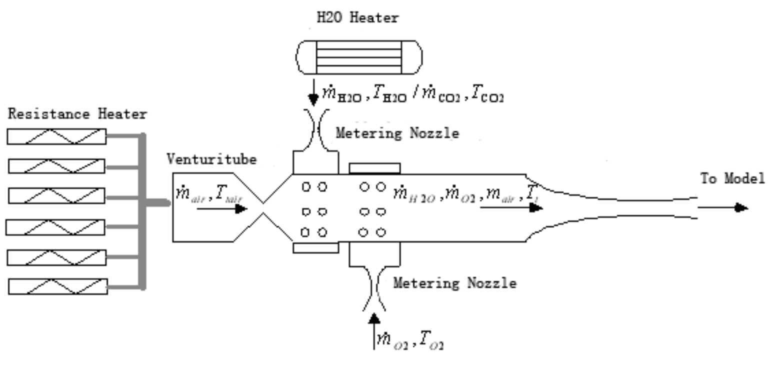


Figure 1. Production of simulated vitiated air

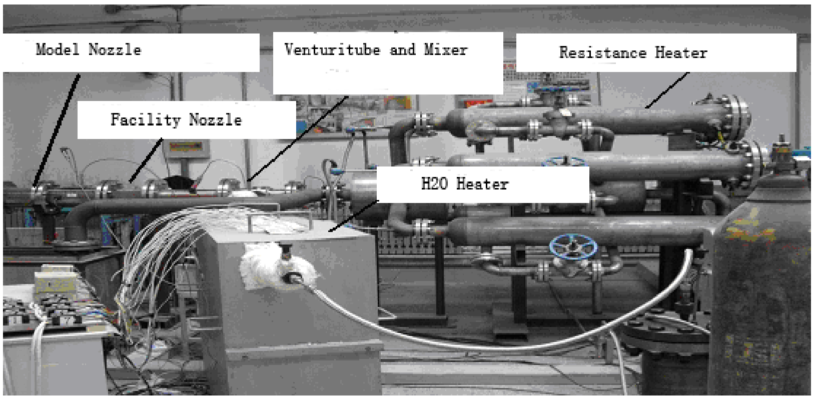


Figure 2. The picture of compared system

Table 1. Index of specific supplied air

Designed parameter	electric heater	H_2O heater	CO_2 supplied	O_2 supplied
Mass of flow	0.5~1.5kg/s	20~150g	30~90g	7~100g
Total temperature of flow	600~1000K	<700K	<350K	≈300K
Time of supply	>30s	>5s	>5s	>5s

2.2 Model of Combustor

A two-dimensional nozzle of nominal Mach 2.0 was used to accelerate airflow before enter into supersonic combustor model. The model of combustor used in test of compare performance of clean air and vitiated air was showed the schematic of combustor Figure 3. Total length of combustor is 770 mm. The combustor was composed by a constant cross-section 40 mm × 30 mm isolator, a single full-width cavity flame-holder, and expansion section. There was a backwards step on the up wall of isolator exit. The expansion section had 2-degree divergence up to exit on the up wall, and the width was constant. The fuels were injected perpendicularly from the injector orifices at the front and base of cavity, and the power of 12 J spark igniter used to ignite was located at the bottom of cavity. The flame holder of cavity and spark igniter was distributed on the down-wall of expansion section. The inlet of model combustor connected to planar facility nozzle with Mach 2 at exit. According to require different injectors and fuels (hydrogen or ethylene) could be used in test, and fuel equivalent ratio can be changed through adjusting injection pressure.

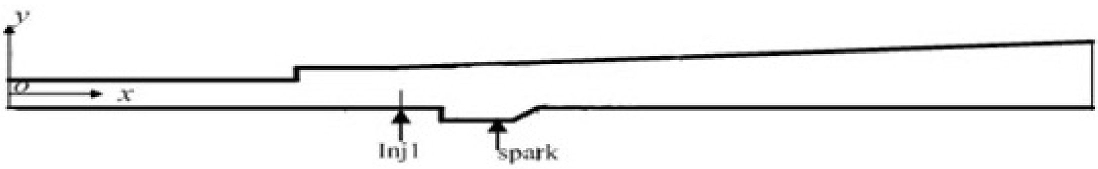


Figure 3. Model of combustor

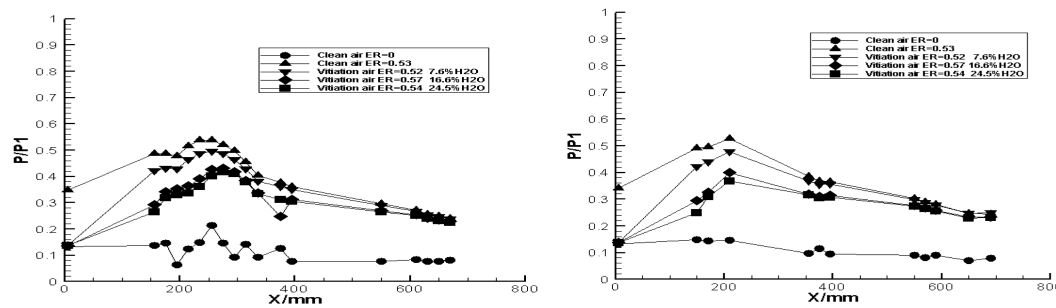
3. Results and Discussions

The type test cases showed in Table 2.

Table 2. The case of vitiated effect on the fuel hydrogen with H_2O and CO_2

Case	Contaminations	$\Phi(H_2)$	Combustion status
1001	Clean air	0．53	Steady
1002	7．6%H_2O	0．52	Steady
1003	16．6% H2O	0．57	Steady
1004	24．5% H2O	0．54	Steady
2001	Clean air	0．42	Steady
2002	7．4%H2O	0．42	Steady
2003	7．4% CO2	0．42	Steady
2004	8%H2O　7.6%CO2	0．41	Steady

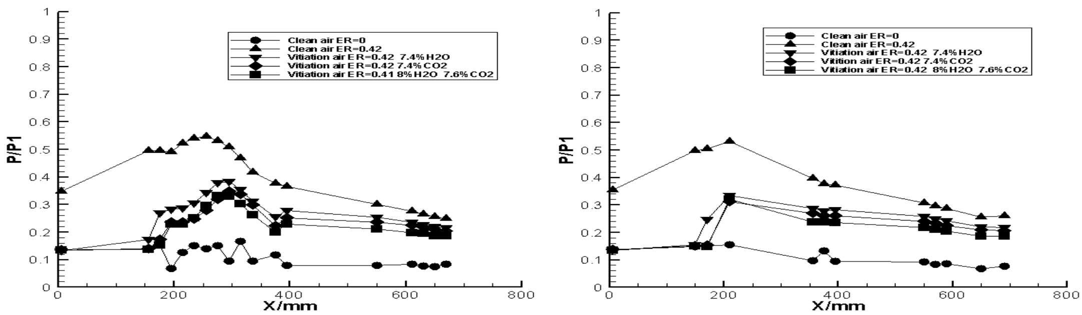
The combustion dimensionless up-wall and bottom pressure distribution of manifold H_2O species percent vitiated air was showed in the Figure 4, which inlet of isolator was the origin coordinate. As the Figure 4a, 4b showed, the combustion was steady for clean air and H_2O species vitiated air. The highest wall pressure was clean air.



(a) Up-wall pressure (b) Bottom-wall pressure

Figure 4. Comparison of the wall pressure

With increased mole fraction of H_2O species vitiated air, from 0%, 7.6%, 16.6% to 24.5%, the wall pressure of combustor were reduced. In climbed phase of wall pressure of combustor, the wall pressure were reduced extent about 10% to 18%. After the cavity, the difference of wall pressure was inclined to decrease along axial of combustor. These showed: Because of H_2O species introduced, the effect of species vitiated was very obviously on the highest wall pressure of combustor.



(a) up-wall pressure (b) bottom pressure

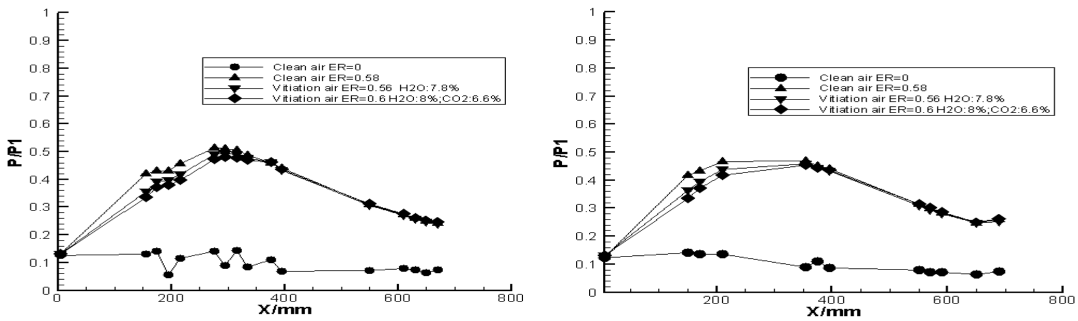
Figure 5. Comparison of the wall pressure

The combustion dimensionless up-wall and bottom pressure distribution of manifold H_2O and CO_2 species percent vitiated air was showed in the Figure 5, which species percent changed from 0%, 7.4% H_2O,7.4% CO_2 to 8% H_2O+7.6% CO_2. As Fig5a, 5b showed, the highest wall pressure was clean air. The wall pressure of 7.4% H_2O vitiated air was decreased about 18% than clean air. However, the wall pressure of 7.4% CO_2 vitiated air was lower than 7.4% H_2O vitiated air. It was lowest that the wall pressure of 8% H_2O+7.6% CO_2 vitiated air.

After the cavity, the difference of wall pressure was inclined to decrease along axial of combustor. For the hydrogen fuel, the wall pressure effect of CO_2 species was higher than H_2O species.

Table 3. The case of vitiated effect on the fuel ethylene with H_2O and CO_2

Case	Contamination	Φ (C_2H_4)	Combustion status
3001	Clean air	0.58	Steady
3002	H_2O: 7.8%	0.56	Steady
3003	H_2O: 8%; CO_2: 6.6%	0.6	Steady



(a) up-wall pressure (b)bottom-wall pressure

Figure 6. Comparison of the wall pressure

In Figure 6, using ethylene fuel, the normalized up-wall and bottom pressure distribution of manifold species vitiated was showed respectively 0%, 7.8% H_2O, and 8% H_2O+6.6% CO_2. As Figure 6a, 6b showed, the wall pressure was increased and the top in the isolator and middle part of combustor. Then, the wall pressure was deceased with flow accelerated in the divergence part of combustor. The difference of wall pressure was obviously in pressure climbed phase, and the highest of wall pressure of combustor was clean air. With 7.8% H_2O species vitiated air; the wall pressure of combustor was relatively lower than clean air. The lowest wall pressure was vitiated air with 8% H_2O+6.6% CO_2.

To compare front result of analyze, the conclusion was: the highest wall pressure of combustor was clean air for the airstream with manifold contaminated species. Furthermore, the wall pressure of combustor was deceased with contaminated species percent increased. The effect of CO_2 contaminated species was more signally than H_2O.

The reason of pressure difference of combustor was multifarious. On the one hand, in the reaction of combustion H_2O could be decomposed to the radical H, O, OH, which would promote ignition and combustion. The CO_2 was inertia in burnt reaction of hydrogen fuel. On the other hand, the difference of property of H_2O and CO_2 species introduced, some air species were altered by vitiated species, such as N_2, O_2, and then there was difference specific heat of clean and vitiated air. Integrated all complication, the CO_2 species was showed signally effect on the combustor.

4. Numerical Simulated

The scramjet test carried through in the ground, limited by condition of test and measure instrument, couldn't acquire all the information of flow field and performance of scramjet of the effect of vitiated species. So the numerical simulated was needed to research the effect of vitiated species. The implicit expression and couple was applied to solve the two-dimension steady-state field. The turbulent mode of Realizable k-ε was applied, used second order upwind and standard wall function. Meantime, the effect of variable specific heat was considered.

4.1 Numerical Method Verify

The numerical method was needed to verify, in order to simulate flow field true. Choose the case 1001 as test case to compare with the result of numerical. The initial condition was given in the Table 4.

Table 4. The parameter of flow and fuel

Case	Mach number	Pt(Pa)	Tt(K)	ER(H2)	Flow species
1001	2	750000	799	0.53	O_2: 0.233 N_2: 0.767

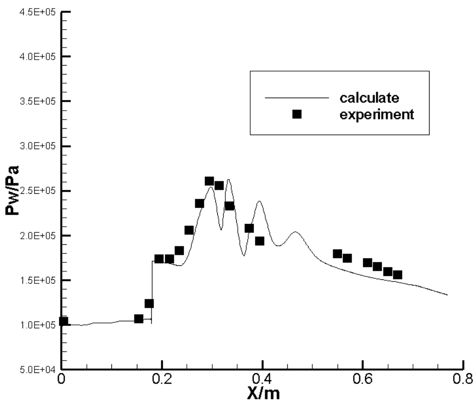


Figure 7(a). Up-wall pressure compare

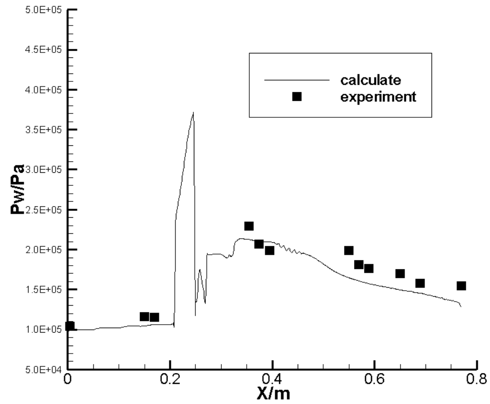


Figure 7(b). Bottom-wall pressure compare

It was discovery consistent that the result of test and numerical from Figure 7(a) and Figure 7(b). So the numerical method could be used to simulate the flow field of scramjet.

4.2 Combustor Model and the Numerical Simulate Test Case

The combustor model applied to numerical simulate was showed in Figure 1. The test cases of numerical simulate were given in Table 5.

Table 5. The parameter of flow and fuel

Case	Tt	Pt	ER(H2)	Flow species
2001	786K	795KPa	0.425	O_2:0.21; N_2:0.79; H_2O:0; CO_2:0
2002	781K	756KPa	0.42	O_2:21; N_2:0.715; H_2O: 0.074; CO_2:0;
2003	794K	790KPa	0.423	O_2:0.217; N_2:0.627; H_2O:0.08; CO_2:0.076
2004	807K	768KPa	0.423	O_2:0.21; N_2:0.716; H_2O:0; CO_2:0.074
2005	798K	765KPa	0.425	O_2:0.202; N_2:0.615; H_2O:0.183; CO_2:0

4.3 The Result Analyzed and Discussed

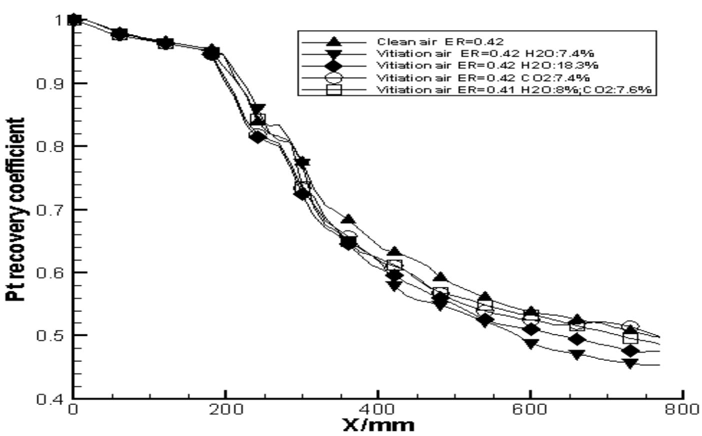


Figure 8. Total pressure recovery coefficient

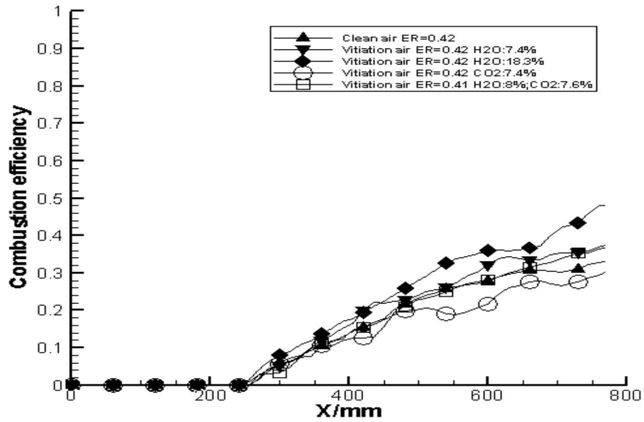


Figure 9. Combustion efficiency

In Figure 8, the total pressure recovery coefficients were compared. The highest value of coefficient was clean air, and the lowest of value of coefficient was the flow with 7.4% H_2O of vitiated species. The result of the flow with 7.4% CO_2 and 8% H_2O+7.6% CO_2 was in middle. By Figure 8 and Figure 9, the highest of combustion efficiency was the flow with 18.3% H_2O of vitiated species. It was explained that the efficiency was calculated used the total temperature. Meanwhile, that showed the present vapor and cracked H, O, OH promoted combustion. The lowest combustion coefficient was the coming flow with 7.4% CO2, and the combustion coefficient of flow with 8% H_2O+7.6% CO_2 was higher than the flow with 7.4% CO_2. That showed the present CO_2 could suppress combustion and decrease the performance of combustor. Considering Fig8 and Figure 9, that was concluded: the major role of vapor cracked H, O, OH was promoted combustion in scramjet and the present of CO_2 could suppress combustion, respectively.

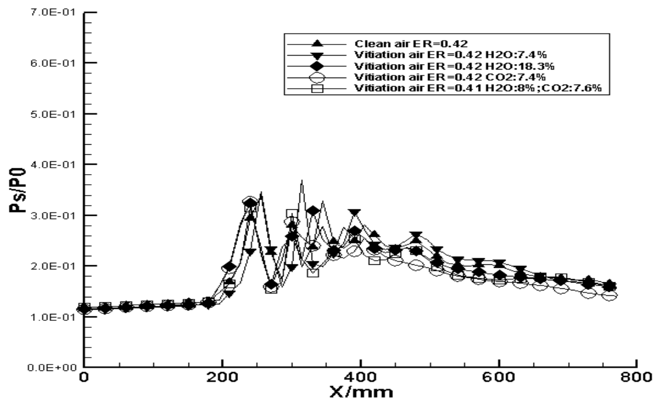


Figure 10. Axial static pressure

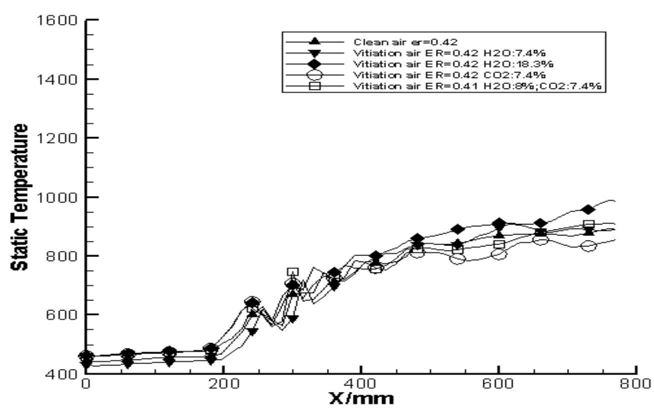


Figure 11. Axial static pressure

In Figure 10, the axial averaged pressure of combustion was compared. The highest averaged pressure was the flow with 7.4% H_2O, and the pressure of flow with 7.4% CO_2 was the lowest. That showed that the certainly present of vapor in the coming flow was positive for the combustion in scramjet. In Figure 11, the axial averaged temperature of combustion was compared. The highest averaged temperature was the flow with 18.3% H_2O, and the temperature of flow with 7.4% CO_2 was the lowest. That could explain the coming flow with 18.3% H_2O taken more caloric joined action than other states. Considering Figure 10 and Figure 11, the thrust of scramjet could be influenced by the flow with the vitiated species, so the effect of vitiated species needed to be considered when the combustion was design.

5. Conclusion

In this article, the vitiated species was simulated to apply addition vitiated species to gas of nozzle exit of direct-connected resistance heated wind tunnel. The effect of vitiated species on the supersonic combustor was investigated used the fuel of hydrogen and ethylene, with H_2O (7.4%, 7.6%, 7.8%, 16.6%, 24.5%) and CO_2 (7.4%, 7.6%) vitiated species, respectively. Then CFD simulations of reacting flow field in the combustor were conducted to investigate the effect of vitiated species of H_2O and CO_2 on the performance of supersonic combustor.

1. The highest wall-pressure of combustion was clean air. The wall-pressure of combustion was decreased with mole fraction of H_2O increased from 0%, 7.6%, 16.6% to 24.5%, pressure decreased markedly in phase of pressure climbed.

2. The combustion dimensionless up-wall and bottom pressure distribution of manifold mole fraction of H_2O and CO_2 species was compared, which mole fraction changed from 0%, 7.4% H_2O,7.4% CO_2 to 8% H_2O+7.6% CO_2. The wall pressure of 7.4% H_2O vitiated air was decreased about 18% than clean air. However, the wall pressure of 7.4% CO_2 vitiated air was lower than 7.4% H_2O vitiated air. It was lowest that the wall pressure of 8% H_2O+7.6% CO_2 vitiated air.

3. The performance of scramjet combustor was compared by numerical analyzed, the coming flow contained vitiated air with mole fraction of 7.4% H_2O, 18.3% H_2O, 7.4% CO_2 and 8% H_2O+7.6% CO_2. The result was the thrust of scramjet could be influenced by the flow with the vitiated species, so the effect of vitiated species couldn't be ignored when the combustion design.

Summarized the result of experiment and numerical, the performance of combustor could be effected by vitiated species, and the evaluation of the performance of scramjet was influenced because of altered performance.

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