Numerical Simulation of Film-cooled Vitiated Air Heater for Direct-connect Scramjet Experiment

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Abstrct

To better understand the combustion characteristics of a vitiated air heater (VAH) in a direct-connect supersonic combustor, we conducted Large Eddy Simulation (LES) using the reactingFoam solver from OpenFOAM. The VAH comprised a GH2/GO2 single coaxial shear injector for heat addition, surrounded by 24 air injectors for air supply and film cooling. By introducing coolant injection, we were able to thermally insulate the combustor wall and promote turbulent motion.

1 Introduction

In the development phase of hypersonic flight vehicles, ground test facilities are crucial. These facilities are constructed in various ways, with operation times ranging from milliseconds to continuous operation. However, the cost of building an experimental facility is proportional to its operable time and the scale of the experiment. During scramjet combustion experiments, combustion instability in the supersonic combustion flow field has been discovered and is being analyzed through both experimental and numerical methods. This low frequency supersonic combustion instability occurs at a few hundred Hz [1-6]. The pulse-type test facilities, which operate for approximately 1ms, are not suitable for capturing and analyzing this periodic instability. The blowdown type test facilities, which have operation times in the order of seconds, offer three options for air heaters that vitiate air with combustion product, air dissociation, and particulates, respectively. Among these options, for laboratory scale combustion experiments, the combustion type vitiated air heater using a rocket combustor and supersonic nozzle is the simplest and cheapest option.

To focus solely on the supersonic combustor and its flow characteristics, the air intake of the vehicle is bypassed by connecting the vitiated air heater directly to the scramjet engine's isolator using a shape transition nozzle [7,8]. In this scenario, we mimic the flow properties after passing through multiple oblique shock waves at the inlet, which can reduce the flow Mach number generated by the vitiated air heater compared to the freestream Mach number. This direct-connect type combustion test device allows for effective supply of high-enthalpy supersonic flow into the supersonic combustor without the need to accelerate the flow into hypersonic speeds. Many supersonic combustion experiments use direct-connect type combustors due to these advantages. Typically, the high-pressure rocket combustor has a circular

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cross-section, while the supersonic combustor has a rectangular or square cross-section for visualization convenience. To connect these structurally mismatched components, the supersonic shape transition nozzle [7,8] is developed.

The design of the combustor for the vitiated air heater is based on the well-known CFD validation case of The Pennsylvania State University [9,10]. To mimic and supply high-enthalpy supersonic flow into the scramjet isolator, the oxygen mass fraction of the combustion product of the vitiated air heater must match the species composition of the standard atmosphere. Therefore, additional air injectors are introduced on the base model combustor, which utilizes a GH2/GO2 shear coaxial injector. From the VAH design perspective, the additional air injectors operate as the main air supply, while the GH2/GO2 shear coaxial injector adds heat to the main air stream. When a separate additional air injection is used, other than the GH_2/GO_2 shear coaxial injector, it can be used as a gaseous coolant for the combustor. Typically, hydrogen, nitrogen, or any other hydrocarbon fuel is used as a coolant with concerns about oxidation. However, as the experimental duration is only about 1-2 seconds and the hydrogen mass flow rate is approximately 5 g/s, hydrogen cannot be employed as a coolant in our case.

During the design process, it was taken into account that injecting the fluid tangentially into the combustor wall through slots or holes could provide thermal insulation between the flame zone and the wall [11]. This technique not only cools the combustor wall but also enhances turbulent motion in the combustion zone, resulting in homogeneous combustion product being supplied to the scramjet combustor. Thus, coolant air injection was employed in the design to achieve these benefits. The configuration of the designed vitiated air heater can be seen in Figure 1.

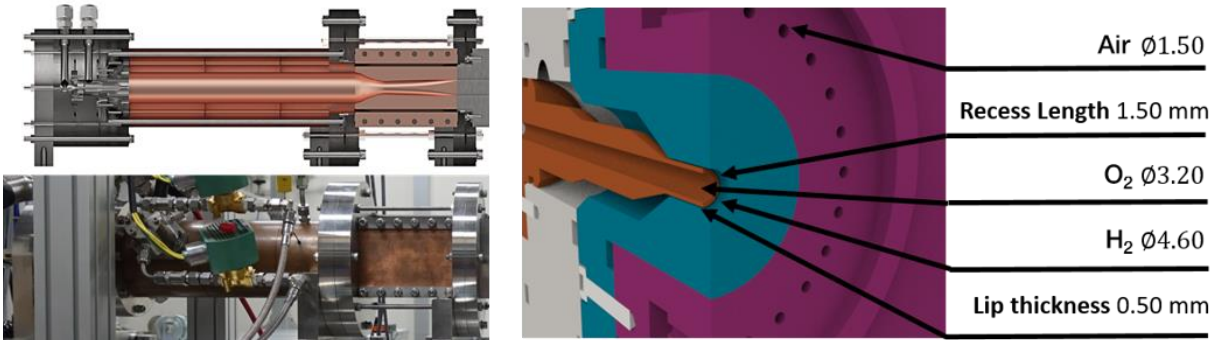

Fig. 1 Configuration of Vitiated air heater and details of injector design

In order to assess the operating performance of the vitiated air heater prior to the supersonic combustion experiment, a performance test is conducted. This test evaluates the combustion and flow characteristics, as well as the thermodynamic properties and species composition inside the combustor. The vitiation effect is often involved in ground scramjet experiments using a blowdown type facility. This effect can impact combustion characteristics such as ignition and flame-holding, as well as mode transition of the dual-mode scramjet and further combustion mode transition. To study these effects, it is important to understand the species composition of the high-enthalpy flow.

2 Methodology

The 3-dimensional numerical simulation used in this study employed a one-equation eddy viscosity Large Eddy Simulation (LES) turbulence model and a Partially Stirred Reactor (PaSR) turbulence-chemistry interaction model with a detailed hydrogen/air chemical kinetics mechanism developed by

Jachimowski. The computational domain contained a total of 13.4 million cells, and a tetrahedral type grid was used due to the complex geometry adjacent to the coolant air injectors.

The rocket-type vitiated air heater is simulated to investigate the performance and flow characteristics of the vitiated air heater for a direct-connect type supersonic combustor. The combustor is designed by tracing the operating condition reversely from the supersonic combustor exit to the vitiated air heater to achieve the ideal expansion at the supersonic combustor exit on the ground test. Theoretically, the exit Mach number of vitiated air heater is set to Mach 2.0. The pressure and temperature at the upstream and downstream of the nozzle were 17.3248 bar and 1,578 K and 2.258 bar and 1,000 K, respectively. The reactant species composition and temperature at upstream of the nozzle were calculated using equations (1) and (2). Equation (1) is formulated to determine the composition of a and b, wherein the oxygen composition of the combusted gas flowing into the supersonic combustor is the same as that of the standard atmosphere. In equation (1), the relation between compositions a and b is shown. In the relation of a and b, 1/2 implies the oxygen injected for the stoichiometric conditions while 1/3.76 is for the compensation of combusted oxygen. The hydrogen and oxygen from the coaxial injector are supplied into the combustor in a certain proportional relation. Therefore, compositions a and b are determined by equation (2) to satisfy the desired adiabatic flame temperature. The mass flow rate of the hydrogen, oxygen, and air injector is calculated as 5.683, 69.043, and 293.525 g/s, respectively. From the measurement of the experiment, the mass flow rate was measured as 4.973, 65.439, and 292.275 g/s, thus the equivalence ratio is changed slightly. In the simulation, the experimentally measured mass flow rate is used.

The quality of the calculation was ensured by comparing pressure history in the combustor with the experimental data, as shown in Fig. 2. The pressure history of the simulation initially showed large amplitude fluctuation due to the shock wave caused by the unrealistic initial condition. To properly develop the injector flow, the pressure inside the combustor was initialized with half the magnitude of that of the injector upstream. The flame was initiated by setting the initial temperature of the combustor to 1,200 K. After the unsteady behavior, the pressure reached its steady state at around 10 milliseconds and showed good agreement with the steady pressure level of the experiment. At 9 milliseconds, the order of the spatial accuracy was changed from first to second to obtain a finer combustion field. The study also includes discussion of the flow interaction between a single shear coaxial injector and multiple film cooling air injectors and the characteristics of the combustion zone.

$$O_2 + 3.76\mathrm{N}_2 + aH_2 + bO_2 \rightarrow O_2 + 3.76\mathrm{N}_2 + aH_2O + \left(b - \frac{a}{2}\right)\mathrm{O}_2$$
$$b = \left(\frac{1}{2} + \frac{1}{3.76}\right)a \quad (1)$$

$$\sum N_i\left[\bar{h}^0_{f,i} - \bar{c}_{p,i}(T_{ad} - T)\right] = 0 \quad (2)$$

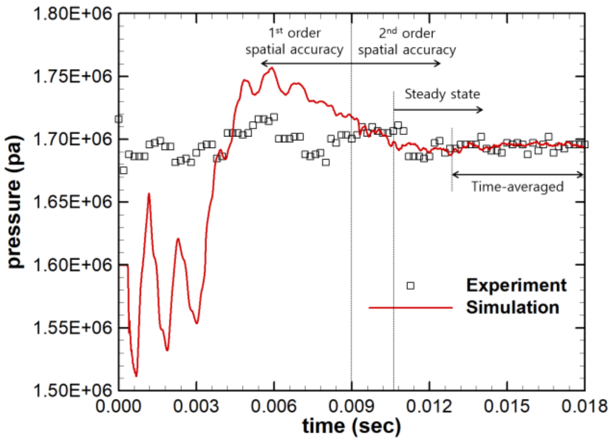

Fig. 2 Temporal pressure development of simulation(line) and steady state pressure history of experiment(symbol) in the combustor

3 Result and Discussion

In figure 3, the combustion parameters such as temperature, OH mass fraction, heat release rate, and flame index of Takeno [13] are shown in the lateral slice. The temperature reaches up to 3,600 K the downstream of coaxial shear injector where the highest OH mass fraction is observed. Also, the low level of OH mass fraction is observed flowing into the recirculation zone. In the heat release rate contour, the outer surface of oxygen core is surrounded by the intense heat release. Likely to the OH mass fraction flowing into the recirculation zone, the intense heat release is again observed in the recirculation zone. In the flame index contour, these can be found that the diffusion flame zone is formed along the region of heat release. Between the coaxial oxygen core and the hydrogen, the diffusion flame is formed and the hydrogen which lost its momentum by the recirculation zone entrained into the recirculation zone. Similar to hydrogen, the amount of the coolant air loses momentum by the recirculation zone, and the oxygen is entrained into the recirculation zone forming the diffusion flame. In the flame index contour, the positive value of the flame index, i.e. premixed flame zone, is formed in a very small region, and the combustion is governed by the diffusive mode. The recirculation zone formed between the coaxial shear injection and the coolant injection holds the flame zone downstream of the injector head.

In figure 4, overall combustion and flow characteristics of vitiated air heater is shown. The time-averaged hydrogen and oxygen mass fraction and u-velocity contour lines are superimposed to identify the overall combustion field characteristics. As mentioned earlier, due to the negative velocity of the recirculation zone, a portion of the coolant air and unburnt hydrogen lose their momentum. This leads the air and hydrogen entrained into the recirculation zone, as we can see the turning contours towards the recirculation zone in the figure 4. These turning contours of oxygen and hydrogen are overlapped in the region of diffusion flame as indicated in the flame index contour in Fig. 3. However, as the Takeno flame index only indicates the spatial gradient of fuel and oxidizer, we can confirm this combusting flow feature by observing the heat release and OH mass fraction contours of Fig. 3. Therefore, due to the coolant injection the injected hydrogen is confined and completely consumed in this region.

Fig. 3 Temperature, OH mass fraction, heat release rate, and the Takeno flame index distribution in the lateral slice. The solid line in the flame index contour indicates the value of zero and the dashed line indicates the negative values of the flame index.

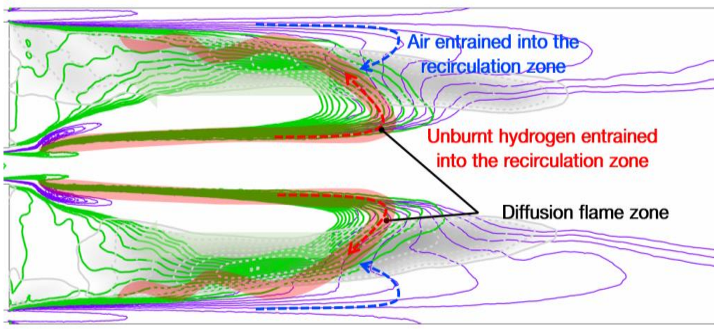

Fig. 4 Time-averaged flow feature of vitiated air heater. Green line indicates the hydrogen mass fraction distribution from 0 to 0.1. Purple line indicates the Oxygen mass fraction distribution from 0 to 0.25. Gray line indicates the negative u-velocity from -200 to 0 (m/s), i.e. recirculation zone.

4 Conclusion

In this study, a large eddy simulation (LES) is carried out using OpenFOAM's reactingFoam solver to evaluate the performance of a vitiated air heater for a direct-connect type supersonic combustion experiment. The vitiated air heater has a single coaxial shear injector and 24 coolant air injectors that protect the combustor wall and promote turbulent eddy motion in the combustion zone. The introduction of coolant injection results in the development of a recirculation zone between the coolant air flow and core flow of the coaxial injector. Intense diffusion flame takes place between the hydrogen and oxygen from the coaxial injector, resulting in complete combustion within one-third of the combustor length. Even though it is not shown in the abstract, the product mass fraction showed a sufficiently uniform distribution at the supersonic nozzle exit.

Acknowledgement

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