초음속 주유동에 수직 분사되는 제트의 비정상 수치해석

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Unsteady Numerical Analysis of Transverse Injection Jet into Supersonic Mainstream

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A series of computational simulations have been carried out for supersonic flows in a scramjet engine with and without a cavity. Transverse injection of hydrogen, a simplest form of fuel supply, is considered in the present study with the injection pressure varying from 0.5 to 1.5 MPa. The corresponding equivalence ratios are 0.167 - 0.50. The work features detailed resolution of the flow dynamics in the combustor, which was not typically available in most of the previous studies. In particular, oscillatory flow characteristics are captured at a scale sufficient to identify the underlying physical mechanisms. Much of the flow unsteadiness is related not only to the cavity, but also to the intrinsic unsteadiness in the flowfield. The interactions between shock waves and shear layer may cause a large excursion of flow oscillation. The role of the cavity and injection pressure are examined systematically

Key Words: Transverse Injection, Supersonic Combustor, Unsteady Flows, Flow Instability

1. Introduction

The success of future high-speed air transportation will be strongly dependent the development of hypersonic air-breathing propulsion engines. Although there exist many fundamental issues, combustor represents one of the core technologies that dictate the development of hypersonic propulsion systems. At a hypersonic flight speed, the flow entering the combustor should be maintained supersonic to avoid the excessive heating and dissociation of air. Thus the residence time of the air in a hypersonic engine is on the order of 1 ms for typical flight conditions. The fuel must be injected, mixed with air and burned completely within such a short time span.

A number of studies have been carried out worldwide and various concepts have been suggested for scramjet combustor configurations to overcome the limitations given by the short flow residence time. Among the various injection schemes, transverse fuel injection into a channel type combustor appears the simplest and has been used in several engine programs, such as the Hyshot scramjet engine, an international program leaded by the University of Queensland.[1] For the enhancement of fuel/air mixing and flame-holding, a cavity is often employed in various supersonic combustion experiments. CIAM of Russia introduced cavities into their engines [2] and U.S. Air Force also employed cavities in the supersonic combustion experiments [3].

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From the aspect of fluid dynamics, transverse injection of fluid into a supersonic cross flow and flow unsteadiness associated with a cavity are interesting topics due to their broad applications in many engineering devices. Thus a number of studies have been carried out, and many of them have great relevance to scramjet engines, but a comprehensive study directly applied to combustor dynamics is rarely found. The obstacles lie in the difficulties in conducting high-fidelity experiments and numerical simulations to observe the dynamical phenomena at time and length scales sufficient to resolve the underlying mechanisms. The present study attempts to achieve improved understanding of the unsteady flow and flow instability in a realistic scramjet combustor configuration employing a transverse fuel injection and a cavity. Little is known for this issue from the previous studies

2. Numerical Formulation

The combustor configuration is assumed to be two-dimensional for computational efficiency. The coupled form of multi-species conservation equations and turbulent transport equations are employed with to analyze the supersonic flows in a scramjet engine. Turbulence closure is achieved by means of Mentor's SST (Shear Stress Transport) model which is based on the k-two-equation formulation [6]. This model is the blending of the standard k-model that is suitable for a shear layer problem and the Wilcox k-ω model that is suitable for wall turbulence effect[7]. Baridna et al. reported that the SST model shows good prediction for mixing layer and jet flow problems, and that it is also less sensitive to initial values [8].

The governing equations were discretized numerically by a finite volume approach. The convective fluxes were formulated using Roe's FDS method derived for multi-species reactive flows along with the MUSCL approach along with a differentiable limiter function. The spatial discretization strategy satisfies TVD conditions and shows high-resolution shock capturing capability. The discretized equations were temporally integrated using a second-order accurate fully implicit method. A Newton sub-iteration method was also used to preserve the time accuracy and solution stability. Since detailed descriptions of the governing equations and numerical formulation are documented in the previous literature [9], it will not be recapitulated here. The numerical methods has been validated against a number of steady and unsteady simulations of shock-induced combustion phenomena that showed good agreement with existing experimental data [10,11].

3. Scramjet Combustor Configuration

3.1 Combustor Configuration

The supersonic combustor considered in this study is shown in Fig. 1. The channel type combustor of 10 cm height and 131 cm length is composed of transverse fuel injection and a cavity. This combustor configuration is quite similar to the Hyshot test model, except for the cavity, in which a swallowing slot is employed to remove the boundary layer from the inlet and the combustor starts with a sharp nose [1].A cavity of 20 cm length and 5cm depth, having an aspect ratio, L/D of 4.0, is employed at 20 cm downstream of the injector.

3.2 Operating Conditions

The incoming air flow to the combustor is set to Mach number 3 at 600 K and 1.0 MPa. This combustor inlet condition roughly corresponds to a flight Mach number 5-6 at an altitude of 20 km, although the exact condition depends on the inlet configuration. Gaseous hydrogen is injected vertically through a slot of 0.1 cm width to the combustor through a choked nozzle. The fuel temperature is set to 151 K. The injector exit pressures are 0.5, 1.0 and 1.5 MPa, and the overall equivalence ratios are 0.167, 0.33 and 0.5.

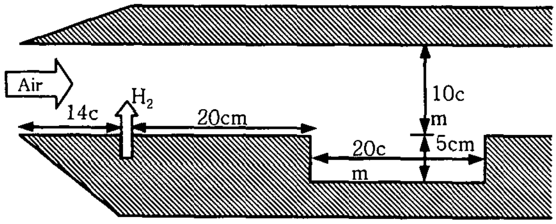

Fig. 1 Frontal part of the scramjet combustor

3.3 Combustor Conditions

A total of 936×160 grids are used for the main-combustor flow passage, and 159161 grids for the cavity. The grids are clustered around the injector and the solid surfaces and the injector. 54 grid points are included in the injector slot and the minimum grid size near the wall is 70 m. All the solid surfaces are assumed to be no-slip and adiabatic, except for the upper boundary. For convenience and reduction of the number of grid points required to resolve the boundary layer, the upper boundary is assumed to be a slip wall, which is equivalent to the flow symmetric condition in the present configuration. Extrapolation is used for the exit boundary. Time step is set to 6 ns according to the minimum grid size and the CFL number of 2.0. Four sub-iterations are used at each time step.

4. Results and Discussion

Numerical simulations were carried out for the cases with and without cavity for three different injection pressures of 0.5 1.0 and 1.5 MPa. The following sections will discuss the results for each case. All the cases were run for 6 ms starting from the initial condition, which is longer than the typical test time of the ground based experiments. The plots of the instantaneous flowfields shown in the followings were taken at 5 ms

4.1 Injection Flow without Cavity

Instantaneous temperature fields for the cases of non-reacting flows without a cavity are plotted in Fig. 2. For the injection pressure ratio of 5.0, the flow field around the injector seems to be quite stable, but a flow disturbance is observed at the location around 40 cm where the first reflected shock wave interacts with the shear layer between the fuel and air flows. The disturbance propagates upstream through the shear layer, but can not reach the injector. Thus the injector flow remains stable and the fuel flow is located very close to the lower surface. The mechanism of the shear layer instability, which is triggered by the impinging oblique shock wave, seems to be the one studied by Papamoschou and Roshko[12].

For the injection pressure ratio of 10.0, disturbance was generated during the early stage of the computation in a manner similar to the case of the injection pressure ratio of 5.0. However the disturbance propagates upstream and triggers the injector flow to become unstable. As a result of this interaction, a large portion of the flow area becomes subsonic and the injector flow oscillates strongly. This unstable motion leads to a higher fuel penetration and the fuel/air mixing is strongly enhanced. This injector flow instability mechanism has been observed by Papamoschou and Hubbard [13]. Ben-Yakar et al. also observed essentially the same unstable injection jet in their supersonic combustion experiment [14]. For the injection pressure ratio of 15.0, the injector flow instability is getting stronger and oscillatory flows are observed in the entire combustor field. Thus the fuel penetrates around the middle of the combustor and the fuel/air mixing is greatly enhanced.

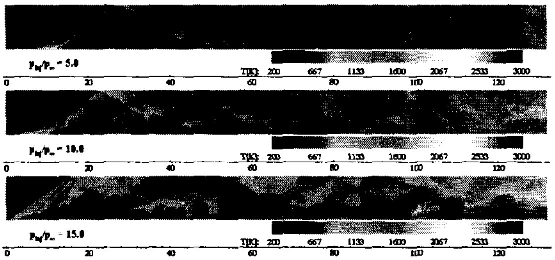

Fig. 2 Instantaneous temperature fields at 5 ms for the case without cavity.

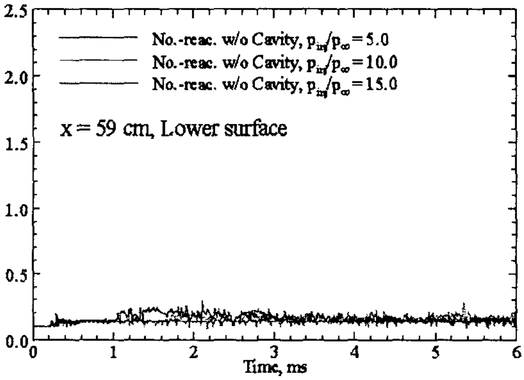

Fig. 3 Time history of pressure for the case without cavity.

Figure 3 shows the temporal variation of the pressure at the location, of x=59 cm from the leading edge of the lower surface. This location is 5 cm downstream of the end of cavity, and is selected because it may reflect all the upstream influences from the injector and cavity. The pressure variations in Fig. 4 reflect the instability characteristics discussed above. The curve for the injection pressure ratio of 5.0 shows oscillations generated from the disturbances in the shock wave/shear layer interaction region, but remains nearly stable maintaining the pressure about 0.15MPa. Similar results are obtained for the pressure ratios of 10.0 and 15.0. However, the flowfield becomes strongly unstable at 1.8 ms for the pressure ratios of 10.0 and at 1.0 ms for the pressure ratio of 15.0. These instances are the time when the injector flows become unstable. After some transitional period between 1 to 2 ms, steady oscillations are reached.

Figure 4 shows the frequency spectrum of the pressure oscillation obtained from an FFT (Fast Fourier Transformation) analysis. Since the total computing time is 6 ms, the low frequency portion in the plot is not the dominant instability frequencies. The dominant frequency that can be observed is located in the frequency around 15 kHz observed for the pressure ratios 10.0 and 15.0.

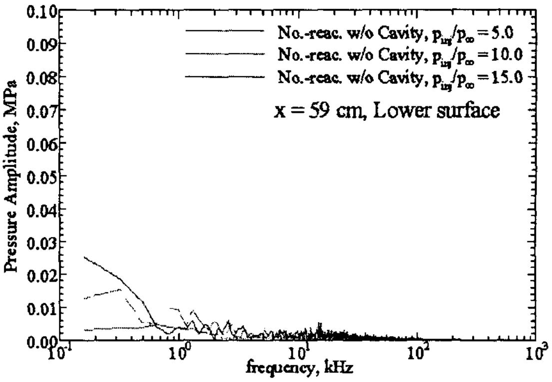

Fig. 4 Frequency spectrum of pressure for the case without cavity.

4.2 Injection Flow with Cavity

Figure 5 shows the instantaneous temperature fields for the case of non-reacting flows with a cavity. The cavity plays an important role in disturbing the flow field and mixing the fuel and air. What is different from the cases without cavity is that the cavity generates disturbances which in turn trigger the injector flow to become unstable even for the case with a low injection pressure ratio of 5.0. Thus, the injector flow becomes unstable for all the pressure ratios under conditions with a cavity. The fuel penetration and fuel/air mixing seems to be enhanced by the oscillating mechanism of the cavity.

Figure 6 shows the plots of the pressure variation at the location of x=59 cm. For all the three injection pressure ratios, the injector instability is triggered by the cavity induced instability within 1 ms, which is around the half of the value for the cases without a cavity. Also the pressure fluctuation is much stronger and the pressure level is maintained slightly higher than the cases without a cavity.

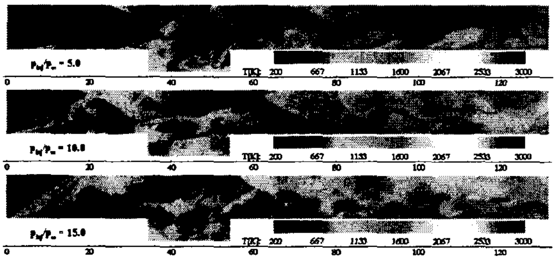

Fig. 5 Instantaneous temperature fields at 5 ms for the case with cavity.

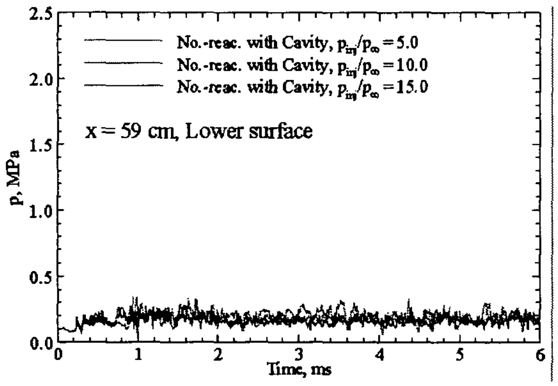

Fig. 6 Temporal variation of pressure for the case of non-reacting flows with cavity.

Figure 7 shows the frequency spectrum for this case. Unlike the above case, the dominant frequency is not at 15 kHz, but around 1.5~2.5 kHz and 4-6 kHz, although there are some dependency on the injection pressure ratio. The expected cavityoscillation frequencies from Rossiter's semi empirical formuladiscussed by Ben-Yakar and Hanson [15] are 1.9 kHz for the first mode and 4.5 kHz for the second mode for the flow conditions in this study. Thus the present computational simulations give quite satisfactory results, considering the complex flow structures involving shock waves and fuel injection.

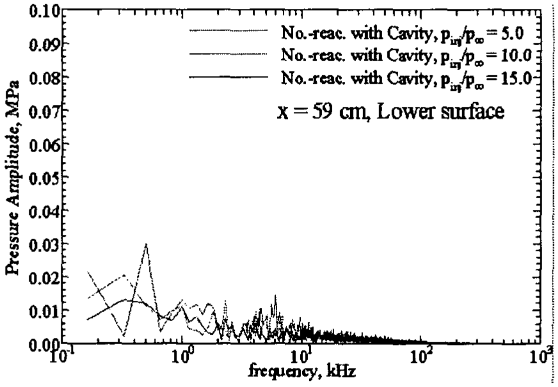

Fig. 7 Frequency spectrum of pressure for the case of non-reacting flows with cavity.

5. Conclusions

The flow dynamics in a scramjet combustor was carefully studied by means of a comprehensive numerical analysis. The present results show a wide range of phenomena resulting from the interactions among the injector flows, shock waves, shear layers, and oscillating cavity flows. As a conclusion of the present study, new findings can be summarized as follows.

1) Strong unsteady flow characteristics were identified for a scramjet combustor. The work appears to be the first of its kind in the numerical study of flow oscillations in a supersonic combustor.
2) Large flow disturbances can be generated by shear layer instability that may be triggered by the interactions with shock waves.
3) The roles of the cavity as a source of disturbance for the transverse jet and fuel/air mixing enhancement were clarified.
3) For all the cases studied herein, instability caused by the cavity seems to override the shear layer instability caused by the shock-wave/shear-layer

interactions when both instabilities are present.

4) Transverse injected jet may remain stable without disturbance, but can be triggered to become unstable with disturbances from a shear layer or a cavity. Disturbed transverse injected jet has deeper penetration and improved fuel/air mixing than the stabilized one. A more careful study is necessary to characterize the stability of transverse injection jets.

References

[1] Centre for Hypersonics - HyShot Scramjet Test Programme, http://www.mech.uq.edu.au/hyper/hyshot/

[2] McClinton, C., Roudakov, A., Semenov, V. and V. Kopehenov, "Comparative flow path analysis and design assessment of an axisymmetric hydrogen fueled scramjet flight test engine at a Mach number of 6.5," AIAA Paper 96-4571, VA, Nov. 1996

[3] Mathur, T., Gruber, M. Jackson, K., Donbar, J., Donaldson, W., Jackson, T and Billig, F., "Supersonic Combustion Experiments with a Cavity-Based Fuel Injector, Journal of Propulsion and Power, Vol.17 No.6, 2001, pp.1305-1312.

[4] Choi, J. Y., Jeung, I. S. and Yoon, Y., "Numerical Study of SCRam-Accelerator Starting Characteristics," AIAA Journal, Vol. 36, No. 6, 1998, pp. 1029-1038.

[5] Smith, G. P., Golden, D. M., Frenklach, M.,Moriarty, N. W., Eiteneer, B., Goldenberg, M., Bowman, C.T., Hanson, R.K., Song, S., Gardiner Jr., W.C., Lissianski, V.V., and Qin, Z., GRI-Mech, http://www.me.berkeley.edu/gri_mech/

[6]. Menter, F. R., "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Application," AIAA Journal, Vol. 32, No. 8, 1994, pp.1598-1605.

[7] Wilcox, D. C., Turbulence Modeling for CFD, DCW Industries, La Caada, CA, 1993.

[8] Bardina, J. E., Huang, P. G., and Coakly, T. J., "Turbulence Modeling Validation," AIAA 97-2121, 1997.

[9] Choi, J.-Y., Jeung, I.-S. and Yoon, Y., "Computational Fluid Dynamics Algorithms for Unsteady Shock-Induced Combustion, Part 1: Validation," AIAA Journal, Vol. 38, No. 7, July 2000, pp.1179-1187.

[10] Choi, J.-Y., Jeung, I.-S. and Yoon, Y., "Unsteady-State Simulation of Model Ram Accelerator in Expansion Tube," AIAA Journal, Vol. 37, No. 5, 1999, pp.537-543.

[11] Choi, J.-Y., Jeung, I.-S. and Yoon, Y., "Scaling Effect of the Combustion Induced by Shock Wave/ Boundary Layer in Premixed Gas," Proceedings of the Combustion Institute, Vol. 27, 1998, pp. 2181-2188.

[12] Papamoschou, D., and Roshko, A., "The Turbulent Compressible Shear Layer: An Experimental Study," Journal of Fluid Mechanics, Vol. 197, 1988, pp. 453-477.

[13] Papamoschou, D., and Hubbard, D.G., "Visual Observations of Supersonic Transverse Jets," Experiments in Fluids, Vol. 14, May 1993, pp. 468-471., http://supersonic.eng.uci.edu/scramjet.htm

[14] Ben-Yakar, A., Kamel, M .R., Morris, C. I. and Hanson, R. K., "Experimental Investigation of H2 Transverse Jet Combustion in Hypervelocity Flows," AIAA Paper 97-3019, 1997.

[15] Ben-Yakar, A. and Hanson, R. K., "Cavity Flame-Holders for Ignition and Flame Stabilization in Scramjets: An Overview," Journal of Propulsion and Power, Vol. 17, No. 4, 2001, pp.869-877.