超音速流における二段燃焼による保炎の研究

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Chapter 1: Introduction

For the successful development of supersonic propulsion devices the knowledge of ignition and flame stabilization is needed. Since flows within such devices are supersonic, the mixing and reaction times are drastically reduced as compared to the situation within subsonic combustors. A direct implication of the significantly reduced mixing and reaction times is the enhanced sensitivity of the flame stabilization processes in terms of extended ignition delays and the greater propensity of the bulk flame to be extinguished or blown out. Furthermore, the use of conventional bluff-body flame-holders for flame stabilization also tends to generate strong shock waves, which can cause significant pressure loss. On the positive side, the substantial amount of the kinetic energy in the bulk flow can be advantageously utilized to facilitate reaction when it is converted to thermal energy as the flow is locally slowed down in the flame-holding region.

Hydrogen is well known as the most suitable fuel for supersonic propulsion systems because of its high potential of heat release and rapid reaction with air. Therefore, considerable research has been directed toward hydrogen combustion in supersonic airflow. The main problems that arise in this regard concern: mixing of reactants, ignition, flame-holding, and completion of combustion. To solve these problems, the merit of preburner has been proposed by a few researchers. In such a preburner, hydrogen and air mix and burn before injection into supersonic flow and provide a high temperature mixing zone for ignition. Moreover, the radicals that are produced through precombustion, may in turn promote ignition and enhance combustion.

The present study is an attempt to study the supersonic combustion of preburned hydrogen numerically and experimentally. In this regard, it addresses the essential problems of supersonic combustion such as ignition, flame stabilization and mixing. This study intends to first, solve the problem of ignition and flame stabilization in low
Mach number supersonic airflow by using preburning method. Second, to investigate the combustion mechanism and flame structure of preburned hydrogen in supersonic airflow. Third, to understand the flame stability regime of preburned hydrogen in supersonic airflow. Fourth, to develop a numerical method for computation of supersonic turbulent combustion.

Chapter 2: Equilibrium Combustion at Preburner

In Chapter 2, the combustion in preburner is discussed. It was assumed that the premix of hydrogen and air flows into preburner and burns at the condition of homogeneity. Such steady-state combustion was designated as the “first-stage combustion”. The process under the above condition can be considered as equilibrium combustion. The equilibrium chemistry was used to calculate the equilibrium mole fraction of species and thermodynamic properties. The initial temperature of preburner was set at $T_i = 293$ K. The equilibrium conditions were calculated for a wide range of preburner equivalence ratio, $\phi_p = 0.3-20$ and preburner pressure, $P_p = 0.02-0.2$ MPa. Then, the calculated results for adiabatic temperature and major and minor species mole fraction are given. Furthermore, the effect of pressure on equilibrium is discussed.

Chapter 3: Numerical Method for Supersonic Reactive Flow

In Chapter 3, the numerical method for computation of supersonic turbulent reactive flows is discussed. Reactive flow is a special type of physical phenomenon that encompasses fluid dynamics, chemical thermodynamics, chemical kinetics, and heat transfer. Thus, numerical modeling of reactive flows addresses several of the most important issue of engineering science. In addition to difficulties concern with turbulence model, chemistry model, and so on, the numerical scheme is a problem itself. The stiffness of chemical reaction is an important problem for reactive flow. This difficulty is caused by difference in chemical time scale of species. In order to eliminate this stiffness and at the same time keep numerical stability the species equation and Navier-Stokes equation must be solved in a coupled fully implicit form. Other approach including uncoupled method or point-implicit scheme needs a numerical stability consideration.

A full implicit scheme for turbulent reactive flow was obtained by combining the second order TVD scheme with the implicit lower-upper scheme. The species equations, Navier-Stokes equations and turbulence model are implemented in the numerical scheme and solved in conjunction with full detailed finite chemistry. The ability of the present numerical scheme for supersonic turbulent base flow was investigated. The pressure profile along the centerline and the velocity flow fields of two supersonic streams past a finite-thickness base were well predicted by numerical scheme. Finally, the ability of the adopted turbulence model was demonstrated.
Chapter 4: Numerical Simulation of the Secondary Combustion of Hydrogen Injected from a Preburner into a Supersonic Airflow

In Chapter 4, with regard to a preburner and secondary burning, ignition and flame-holding of hydrogen in supersonic airflow are numerically studied. The physical model is a two-dimensional supersonic flow behind a thick base, with parallel fuel injection from the base. It is assumed that there is a preburner before the nozzle where precombustion of hydrogen and air occurs. The upstream Mach number, pressure, and temperature of the supersonic airflow are chosen as \(M_{\text{air}}=1.5\), \(P_{\text{air}}=0.05\) MPa and \(T_{\text{air}}=293\) K, respectively. The two-dimensional, unsteady, compressible, Navier-Stokes equations in conjunction with Baldwin-Lomax turbulence model as well as combustion chemistry model were solved by numerical method. First, in agreement with previous experiment, the possibility of ignition and flame-holding by preburning was predicted by. In addition, the effect of the preburner equivalence ratio, \(\phi_p\), the pressure of the preburner and the supersonic airflow temperature on flame development were studied. With respect to \(\phi_p\) two regimes of combustion were found. For \(\phi_p < 4.2\) the effect of the radicals on ignition and combustion development was negligible. In contrast, for \(\phi_p > 4.2\) the effect of radicals on ignition and combustion is quite significant.

It was understood that the preburner pressure, \(P_p\), similar to \(\phi_p\) had a significant effect on combustion development. It changed the amount of radical production in the preburner as well as the mass flow rate of the injected gas from the preburner. As \(P_p\) increases, not only the injected amount of \(H_2\) but also radicals increase. There were two extinction limits with respect to the preburner pressure, a lower limit at \(P_p/P_{\text{air}}=0.6\) and an upper limit at \(P_p/P_{\text{air}}=3.0\). The lower limit occurred due to the decrease of temperature by deficiency of hot injected hydrogen in the recirculation zone. On the other hand, the upper limit imposed by reduction of residence time as well as deficiency of radical production in the preburner.

For high temperature air flow, the substantial combustion region is expanded upstream and downstream. The combustion reaction rate is magnified and the flame-holding is enhanced. The combustion efficiency shows that a small percentage of fuel leaves the combustor unburned even in the case of high temperature airflow. However, the combustion becomes more complete with an increase in air temperature.

Chapter 5: Numerical Study of Preburned Hydrogen by High Order Numerical Scheme for Turbulent Reactive Flow

A complicated supersonic turbulent reactive flow including turbulent-chemistry-shock wave interaction demands a high order numerical scheme. In this chapter a fourth-order MUSCAL TVD scheme was developed to include
turbulence model. The modified q-ω turbulence model developed for compressible reactive flow was implemented in high order MUSCAL scheme. A full implicit scheme for turbulent reactive flow was obtained by combining the fourth-order MUSCAL scheme with the efficient implicit lower-upper scheme of Shuen-Yoon. The species equations, Navier-Stokes equations and turbulence model were implemented in the numerical scheme and solved in conjunction with full detailed finite chemistry. First, the numerical scheme was examined by the experimental axisymmetric base flow by Herrin and Dutton. Then, numerical scheme was used to study the hydrogen combustion. A two-dimensional strut was used as flame-holder. The inflow was a two-dimensional supersonic airflow with $M_{in}=1.5$, $P_{in}=0.05$ MPa and a wide range of temperature, $T_{in}=100$-1400 K.

Ignition and flame-holding of hydrogen injected from the base of the strut into supersonic airflow at two conditions of preburning and non-preburning were studied. In preburning method premixture of hydrogen and air burns in a preburner before injection into supersonic airflow. First, ignition and flame-holding were investigated at non-preburning condition. The temperature limit of auto-ignition was predicted and the combustion mechanism was shown. Then, ignition and flame-holding of preburned hydrogen were investigated. It was realized that using preburning method drastically reduces the temperature limit of auto-ignition. The combustion regime at preburning condition was predicted. Furthermore, it was predicted that the preburning just is necessary for ignition, and that after stabilizing the flame the preburner is no longer needed.

Chapter 6: An Experimental Study on Flame Structure and Stability Limits of Preburned Hydrogen in Supersonic Airflow

In Chapter 6, the same phenomenon was experimentally studied. The flame-holding as well as the flame structure was experimentally investigated. A two-dimensional rectangular-cross-section strut was used. The experiment was done at a wide range of preburner equivalence ratio using hydrogen and air flow rate of $Q_{H_2}=50$–1000 Nl/min and $Q_{air}=50$–300 Nl/min, respectively. The initial temperature and pressure of mixture of hydrogen and air were $T_0=288$–297 K and $P_0=0.1$–0.6 MPa, respectively. A high sensitive thermocouple and a transducer measured the inner temperature and the pressure of preburner, respectively. The test duration was 20 sec, and total pressure and total temperature were 0.45–0.5 MPa and 450–850 K, respectively. The main airflow Mach number was maintained at 2.5. For each experiment, the flame or the combustion development was recorded by a video camera. In addition, OH distribution was taken by a DEP XX1420AA high speed intensified camera. Temperature field was measured by using high sensitive 40%PR thermocouple with a diameter of 0.5 mm. Sampling was done by using a setup for taking sample and then analyzing by a chromatograph analyzer system.

It was found that the preburning is a reliable method for ignition and flame-holding. Without preburning, auto-ignition was not observed up to $T_0=850$ K. The preburning just was necessary for ignition, and after stabilizing the flame, it was possible to turn off the preburner at all tests. Flame stability limit of preburned hydrogen in supersonic
airflow was obtained and compared with numerical simulation. Both experiment and numerical simulation showed that the flame stability limit strongly depended on the preburner equivalence ratio and the total temperature of supersonic airflow.

Chapter 7: Conclusion

Numerical and experimental studies on combustion of preburned hydrogen in supersonic airflow were done. These studies mainly were concerned with ignition, flame stabilization, flame structure and combustion mechanism as well as numerical method for reactive flows. First, the possibility of ignition and flame-holding by preburning method was predicted. It was shown that the temperature limit of auto-ignition is drastically reduced by using the preburning method. In addition, the effect of the preburner equivalence ratio, $\phi_F$, the pressure of the preburner and the supersonic airflow temperature on flame development were studied. It was realized that each of these three parameters had significant effects on flame-holding and combustion development. Furthermore, flame stability limits of preburned hydrogen were predicted by numerical simulation as well as experiment.
審査結果の要旨

超音速から極超音速までの広い飛行速度で作動するスクラムジェットの研究開発が進められているが、エンジン内の超音速燃焼の制御は解決しなければならない大きな課題の一つとなっている。本論文は、予燃焼室を持ったストラットを提唱し、その二段燃焼による保炎メカニズムの解明を数値解析的に行うと共に、実験的にもその有効性を示した研究成果をまとめたもので、全文7章よりなる。

第1章は緒論である。

第2章では、予燃焼室における水素燃料の燃焼性について平衡計算を行っており、当量比による燃焼温度や活性種濃度の変化などを求めている。

第3章では、支配方程式の数値解析法について述べている。変動性、乱流および素反応過程を加味し、十分な精度を確保するために、各種計算法を組合せ活用する工夫を行っている。

第4章では、後向きステップ背後の超音速乱流燃焼の数値解析を行っている。二つの強い反応領域を持つ特徴的構造、予燃焼室から供給される活性種の保炎への影響、火炎の吹き飛びメカニズムなど明らかにしており、有用な知見である。

第5章は、二次元三角柱状の予燃焼室付きストラット後流の燃焼数値解析を行っている。予燃焼室の燃焼条件が二次燃焼に与える影響を詳細に検討すると共に、ストラットから噴射される高温水素の自着火範囲、水素流量による火炎構造の変化、火炎の吹き飛びのメカニズムなどを明らかにした。特に、ストラット後流のせん断層における混合効率に着目し、局所的反応素過程との関係を示しており、重要な成果である。

第6章は、超音速燃焼実験を行って、第5章の数値解析結果と比較検討した。実際の予燃焼室では、化学平衡に達していないことが定量的に完全な一致を困難にしているが、二つの強い反応領域を持つ構造や、超音速空気流の全温による保炎範囲の変化など、実験と計算は定性的に一致することを明らかにした。

第7章は結論である。

以上要するに本論文は、予燃焼室を設けたストラットの保炎のメカニズムを明らかにすると共に、本ストラットの有効性を理論的実験的に示したもので、極超音速飛行用推進エンジンの設計に有用な指針を与えるものであり、航空宇宙工学・燃焼工学の発展に寄与するところ少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。