램제트 엔진의 점화 천이에 관한 연구

H. G. Sung* · Vigor Yang**

Ignition Transient Mechanism in an Entire Integrated Rocket Ramjet Engine

성홍계* · Vigor Yang**

ABSTRACT

The numerical analysis, including chemical reaction of an entire ramjet engine is studied to understand the ignition transient mechanism and the dynamic characteristics of the Integrated Rocket Ramjet System comprehensively. Details of how a subsonic combustion environment is established from the supersonic ram air after removal of the inlet port cover, are examined during the ignition transient. Various physical processes are investigated systemically, including ignition, flame propagation, flame dynamics, and vorticity evolution.

Nomenclature

P	Pressure
R_e	Reytnolds number
S	flame speed
T	temperature
t	time
u, v	velocity

Greek Symbols

β	scaling factor
Φ	equivalence ratio
τ_t	turbulent time scale

Subscripts

j	spatical coordinate index
L	laminar property
M	model value of experiment
R, ref	reference value
rms	root mean square
t	turbulent property
u	unburned fuel

Superscripts

′	fluctuation

Ⅰ. Introduction

This study consists of three parts. The first part explains the flow transient mechanism during the transition from rocket booster to ramjet sustainer1. The second part details the ignition transient mechanism of a ramjet

* 국방과학연구소(Agency for Defence Development)
** The Pennsylvania State University

engine while the combustion dynamics of a stable combustion is the last part. The second part is discussed in this paper, while the first part is addressed in previous paper[1].

The major issues of this paper are:

- Fuel spreading mechanism and flame propagation.
- The establishment of a subsonic combustion environment during flame propagation.
- Flame dynamics during ignition transition.

II. Ignition Transient Mechanism

In going from the rocket boost phase to the ramjet sustain phase, the transient mechanism of the IRR is relatively complicated after the inlet port cover is opened, since the flow must adjust from supersonic at the ramjet inlet to subsonic in the combustor. An important task of the IRR is to establish subsonic combustion by achieving a normal shock as the terminal shock in the diffuser with sufficient pressure recovery. But the terminal shock disappears after opening the inlet port cover. Moreover, the supersonic ram air occupying the combustor decreases the residence time of the flow, which may aggravate the ignition of the ramjet fuel and may allow flame flashback. The major concerns regarding stable ignition are how the fuel spreads uniformly in the combustor, how the ignition energy is supplied to the fuel, and how the subsonic combustion environment is established.

Another problem in transitioning to the ramjet phase is that the coupling of unsteady motions between the inlet and the combustor may cause unstable combustion and lead to flame blow-off or flashback. Typically, these couplings are very complex and strong during the ignition transient stage of the ramjet engine, since neither the terminal shock nor the combustion of the fuel has reached equilibrium. Thus, unsteady fluctuations in the combustion chamber are expected during the ignition transition (Fig. 1).

The results of the previous paper1 are used as the initial conditions for the current calculations so that the ignition transient may be computed with continuity.

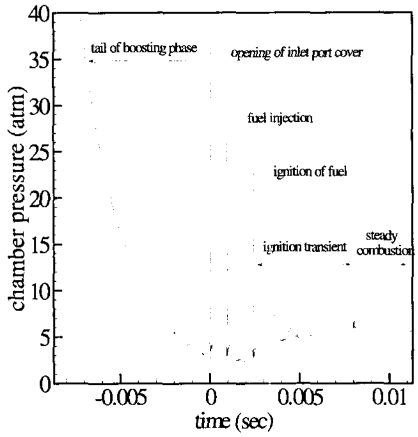


Fig. 1 Chamber pressure history.

A. Fuel Spreading in the Combustion Chamber

The fuel injectors are located at 4 cm ahead of the dump combustion chamber, and the fuel is propane (C_3H_8). The fuel mass flow rate is 0.12 kg/s and the equivalence ratio is about 0.8.

Computationally, fuel is injected into the ram air flow at each computational cell in the injection plane, at whatever rate is necessary to maintain a specified fixed equivalence ratio (e.g., 0.8) given the current ram air flow rate at any given time. In the physical equivalence ratio to this computational injection scheme, the fuel injection orifices are also assumed to be chocked, so that the fuel injection rate is not directly affected by the local pressure.

Fig. 2 shows the fuel spreading and the time evolution of a ring vortex in the combustor. As expected, the fuel stream basically follows the trajectory of the cold ram air, so the fuel spreads into the

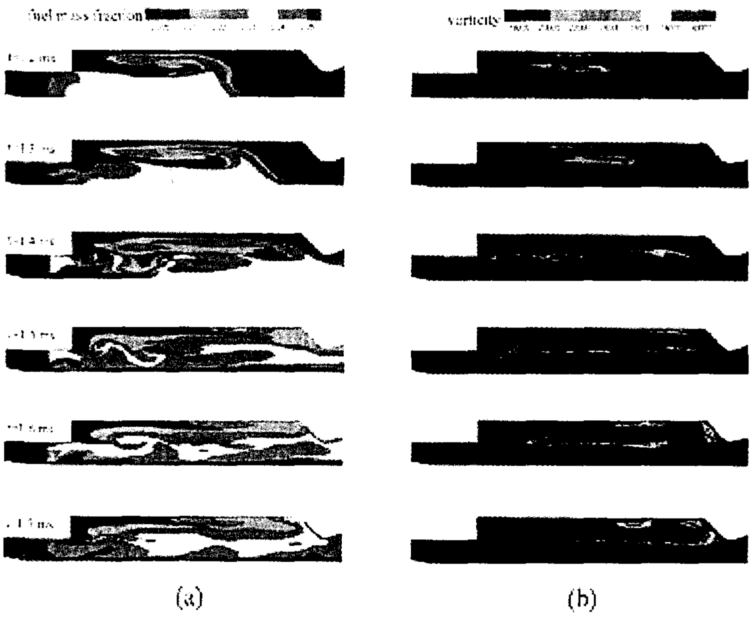


Fig. 2 Ramjet fuel spreading and vorticity fields before ignition of the ramjet fuel.

combustion chamber in the same way as the high-speed ram air which dominates the combustor flow field during this time. Initially, the flow expansion of the ram air plays a major role in the penetration of fuel into the recirculation zone.

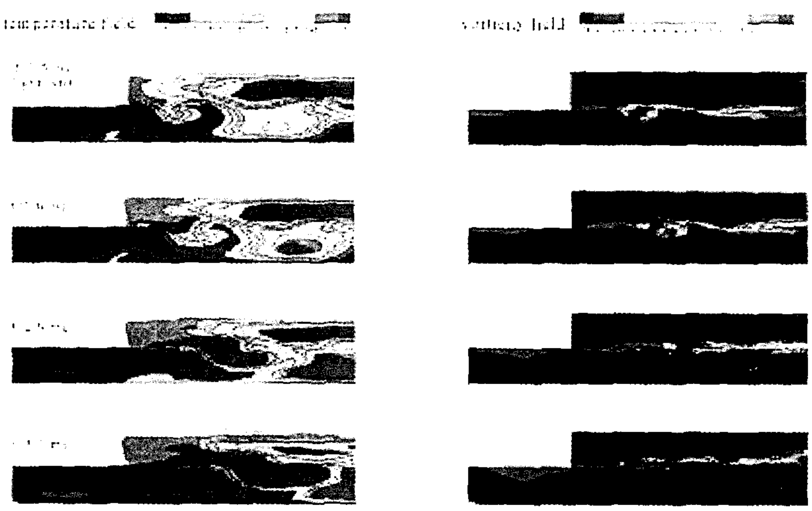
After that, vortex roll-up from the edge of the backward facing step is the next important factor in fuel spreading. Vortex roll-up provides large-scale vortical structures which supply energy for the cascade of turbulence kinetic energy from large eddies to small eddies, and the turbulence motions more evenly distribute fuel in the shear layer. Initially, in the flowfield created by expansion of the supersonic ram air into the combustor, penetration of fuel into the recirculation zone is also enhanced by the convection of fuel-laden vortical fluid from the downstream region back along the combustor wall. Fluctuations in the fuel field are observed near the ends of the injection plane (i.e., near the inlet wall and the centerline). The fuel distribution fluctuates near the inlet wall and center region as the oscillating terminal shock modulates the vortical boundary layer flow there. The fuel near the center region is evolving due to the secondary vortex caused by the flow separation behind the ram core spike. Since the motion of vortices affects the fuel spreading in the entire domain, the dynamic behavior of vorticity in the flow is very important. Fig. 2b shows the evolution of the vortices near the entrance to the combustion chamber. The boundary layer flow near the diffuser wall has axial periodic vorticity due to the oscillations of terminal shock. This vorticity interacts with the shear layer formed by the supersonic jet of cold ram air entering the combustor, dominating the periodic formation of large coherent vortical structures. After that, a ring vortex rolls up and then dies out as its energy is cascaded to smaller eddies. At the same time, the fuel is mixed well in the shear layer. The separation vortex near the center region is also transported into the combustion chamber.

B. Flame Propagation

To ignite the fuel, a heat source is located near the backward step of the combustion chamber, and heat is supplied until the gas temperature reaches the auto-ignition temperature (e.g.,1500 K). Fig. 3a shows the temperature fields just after fuel ignition. The highest temperature region is the ignition position, and there are other regions of the second highest temperature near the wall, due to residual gas from the booster propellant, and near the center region, due to the roll-up of a ring vortex.

The flame starts to propagate into the entire combustion chamber, albeit not uniformly. Flame speed is a strong function of temperature, pressure, equivalence ratio, and convective velocity. For the scenario, the flame propagates rapidly along the surface of the local optimal equivalence ratio, which is constantly changing due to the evolution of vorticies in the shear layer (Fig. 3a).

Fig. 3b shows the vorticity fields. The first ring vortex is generated due to the vortex evolution in the shear layer in the same way (Fig. 2b) as for the cold flow, as indicated in the previous section. Because the flame propagates primarily along the local optimal equivalence ratio surface, the flame front is wrinkled. Moreover, with the large density gradient caused by the chemical reactions, baroclinic generation of vorticity near the flame zone strengthens the ring vortex moving with the wrinkle flame front. Fig. 4b shows the flame propagation in the entire combustion chamber. To determine the primary factor governing the flame propagation, it is valuable to predict the flame speed based on a semi-empirical theory. The flame speed is characterized by unburned



(a)　　　　(b)

Fig. 3 Time evolution of a flame structure and vorticity field during ignition transition.

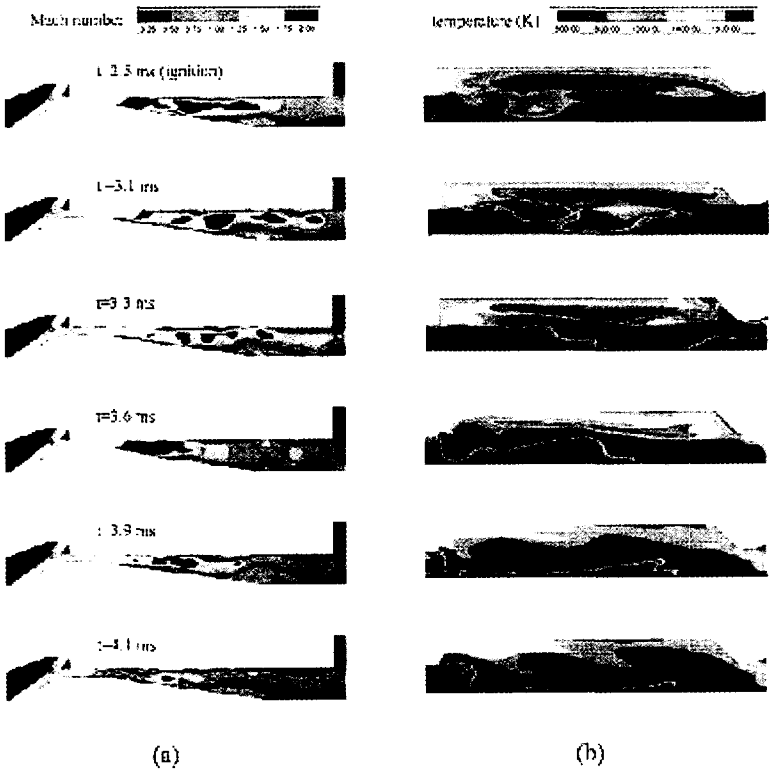


Fig. 4 Establishment of stable subsonic combustion after ignition of the ramjet fuel.

fuel temperature, equivalence ratio, pressure, and turbulence intensity. To estimate a maximum flame speed, it is assumed that the fuel is mixed completely and that fuel temperature is the same as the compressed ram air. Meghalchi and Kecks experimental formulation[2] for laminar flame speed, S_L, is as follows:

$$S_L(T_u, P) = (B_M + B_2(\phi - \phi_M)^2)\left(\frac{T_u}{T_{u_{ref}}}\right)^{\gamma}\left(\frac{P}{P_{ref}}\right)^{\beta} \quad (13)$$

where, $\gamma = 2.18 - 0.8(\phi - 1)$ and $\beta = -0.16 + 0.22(\phi - 1)$. The constants B_M =34.22 cm/sec, and B_2 = -138.65 cm/sec are empirically derived. For the current conditions (5 atmospheres and 0.8 equivalence ratio), the laminar flame speed is 0.44 m/sec. To predict the turbulent flame speed S_t, the Klimov model[3] is applied since turbulent fluctuation velocity(v'_{rms}) is much greater than the laminar flame speed (v'_{rms} = 37 m/sec) in study.

$$\frac{S_t}{S_L} = 3.5\left[\frac{v'_{rms}}{S_L}\right]^{0.7} \quad (2)$$

This yields a value of 34.3 m/sec for the turbulent flame speed. Thus the time required for the flame to reach the nozzle is expected to be about 12 milliseconds, but the computational result is around 1 millisecond (Fig. 1).

This difference can be resolved by considering transport of thermal energy by the mean flow at a velocity of around 300 m/sec, which yields a time of around 1.2 milliseconds required for the flame to reach

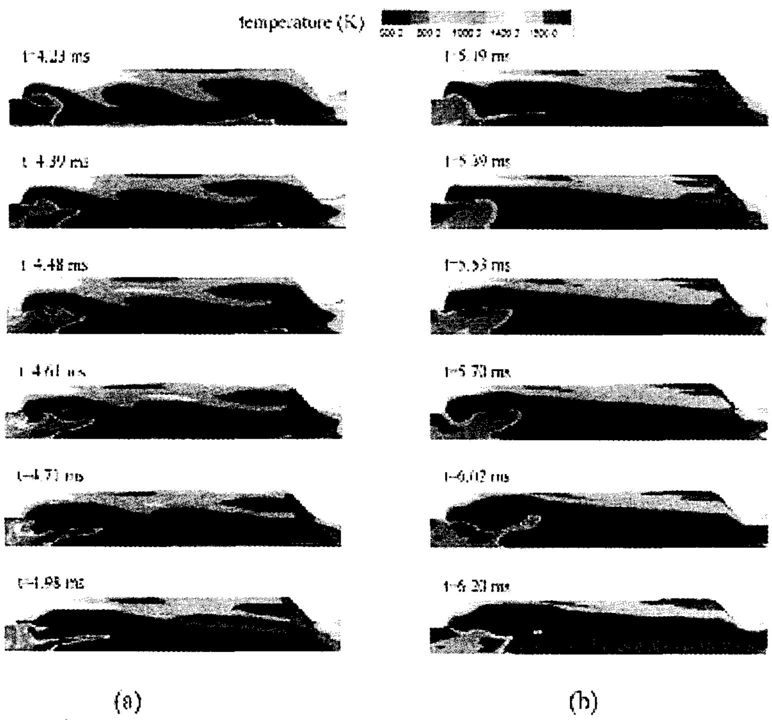


Fig. 5 Flame structure during the first and second cycle of ignition transition.

the nozzle end of the chamber starting from ignition. This means that, initially, flame propagation is dominated not by the diffusive mechanisms of molecular and eddy viscosity, but by convection due to the high speed of the mean flow. However, the importance of convection quickly diminishes when the mean flow is drastically reduced as the terminal shock is reformed due to the increasing chamber pressure from combustion of the fuel.

C. The Establishment of Subsonic Combustion Environment During Flame Propagation

As indicated in Reference 1, the terminal shock is smeared out and a peristalsis of the supersonic core appears after opening the inlet port cover, and the flow becomes supersonic in the combustion chamber. This flow pattern in the diffuser is due to the shock-induced separation as pointed by Bogar et. al.[4], with boundary layers influenced by the intense adverse pressure gradient associated with unsteady oscillation of the shock which modulates the separated boundary layer flow. Because the ramjet operates with a subsonic combustor, an interesting question to ask is, "How is subsonic combustor flow established from the supersonic regime which follows the opening of the inlet port cover?" To answer this question, Fig. 4a gives several snapshots, each of which shows the Mach number in the entire ramjet engine, with each frame synchronized with the corresponding frame from Fig. 4b.

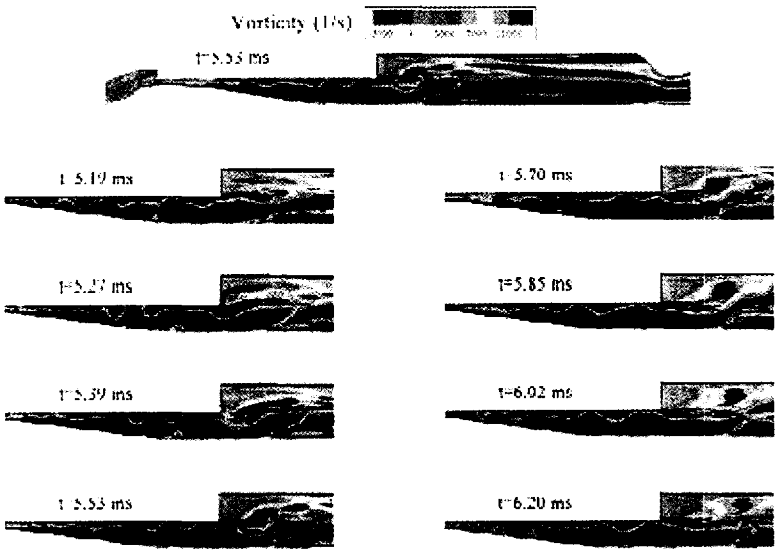


Fig. 6 Vorticity structure during the second cycle of ignition transition.

As the flame propagates, the pressure in the combustion chamber increases. In the supersonic flow region of the inlet diffuser, since the wave (u-c), only propagates toward a combustor, the information regarding this pressure increase due to combustion cannot be delivered upstream through the supersonic core of the inlet diffuser flow. But the wave (u-c), carrying the information can propagate upstream through the subsonic boundary layer. The higher pressure delivered by the wave increases the adverse pressure gradient in the diffuser, which induces flow separation, and thereby decreases the effective flow area in the inlet. So the peristalsis of the supersonic core in the inlet becomes stretched, segregated, and weak.

Finally the upstream-running acoustic wave is able to propagate through the core flow of the inlet, and the terminal shock is reformed due to the increase in the combustor pressure, with subsonic flow downstream of the shock. Another major factor which promotes subsonic combustor flow is the rapid increase in temperature due to combustion of the fuel. This temperature rise yields higher sonic speeds, thus promoting lower Mach number flow. Once a subsonic combustor environment has been achieved in which stable combustion can occur, dynamic flame behavior is still possible due to coupling between vibration of the terminal shock and pressure oscillations in the combustor. This coupling is primarily characterized by the longitudinal acoustic mode.

D. Flame Dynamics

During the ignition transient, the entire flow is highly unsteady, including the flame propagation and the shock recursion, as described earlier. After a large overshoot of chamber pressure during the ignition transient period, the pressure oscillates with relatively smaller amplitude (Fig. 1). The peak-to-peak amplitude of persisting pressure oscillations is about 50% of the amplitude of the first overshoot in pressure, and the amplitude and waveform of the oscillations vary with time. Fig. 5 represents the temperature fields during the first (Fig. 5a) and the second (Fig. 5b) cycle of oscillation after the initial pressure overshoot. The flame sheet fluctuates dynamically and is highly wrinkled during the cycle. The flame sheet bulges somewhat in the radially outward direction and is stretched downstream in the axial direction. Then it begins to roll up near the edge of the backward step under the influence of the shear layer vortices. As the roll-up continues downstream, the flame front propagates radially inward and is grossly stretched so that a sizeable finger or pocket of unburned fuel/air mixture is surrounded by the distorted flame and burned. Soon after this happens, the flame returns to basically its original position and shape. This dynamic motion of flame is closely related to the vortex evolution as shown in Fig. 6. Even though the flame sheet fluctuates periodically, the temperature becomes more uniform throughout the combustion chamber.

Fig. 6 shows snapshots of the vorticity fields during the second cycle of ignition transient. The sign of vorticity is positive when pointing out of the paper, and negative pointing into it. Positive vortices appear near the wall and the upper region of the shear layer in the combustion chamber.

In the turbulent flow, the energy of theses large-scale vortices primarily cascade to successively smaller vortices, and are eventually dissipated by the smallest eddies or convected out of the nozzle. The large-scale vortex to be periodic with the same period as the fluttering of the flame. The terminal shock has a strong influence on the wall boundary layers of the inlet, and, if disturbed by the arrival of an upstream-moving acoustic wave, will initiate a perturbation of the vorticity wave. This perturbation is then convected downstream, creating a transverse, downstream-traveling, wave-like disturbance similar to Tollmien-Schlitching waves transported into turbulent vortices.

After the vortices propagate into the combustion chamber, a large ring vortex is formed if the shedding frequency of the shear layer matches the acoustic frequency of the longitudinal mode. The formation of this vortex roughly coincides with the temporal maximization of the combustion chamber pressure. In other words, the large ring vortex is generated at the same time as the acoustic pressure reaches its maximum (as measured at the dump plane). The shedding frequency of the periodic vortex is closely related to the Strohal number, which saturates to 0.21 at high Reynolds numbers ($10^3<Re<10^7$) for a circular cylinder[5]. Since the mean flow is about 250 m/sec, the period of vortex shedding in a Karman vortex street is about 1.3 milliseconds for our ramjet engine, which is quantitatively similar to 1.2 millisecond calculated from this study (Fig. 1).

The large-scale vortical structures are the dominant influence on the flame dynamics and are also a key in driving combustion instability as pointed out by previous studies.

IV. Summary and Conclusions

The ignition transient mechanism of an IRR system was investigated using the dual time stepping numerical algorithm with preconditioning method. The conservation equations, including finite chemical reactions and a low-Reynolds number κ-ε turbulence model, were solved using an ADI scheme with preconditioned Chakravarthy-Osher TVD.

The computational geometry consists of the entire IRR engine, including the inlet, the combustion chamber, and the exhaust nozzle.

On opening the inlet port cover, to begin the ramjet phase, the terminal shock is smeared out and the flow throughout the entire engine becomes supersonic. However, combustion of the ramjet fuel builds up the pressure and temperature in the combustor such that the combustor flow becomes subsonic and a terminal shock is reestablished in the diffuser. The flame propagation speed, which is initially governed primarily by the mean flow convection of heat, is an important factor in quickly establishing stable (or quasi-steady) combustor flow-for lower flame speed, unstable transient conditions in the combustor are expected to last longer. The vortical motion (mainly within the dump combustor shear layer) strongly affects the fuel spreading and propagation of the wrinkled flame. A ring vortex strongly rolls up at the peak of the chamber pressure oscillation, and the shedding frequency is consistent with the frequency of the Karman vortex street. The initial unstable condition of the combustion yields overshoots in an amplitude of the combustor pressure to over three times higher than the stable combustion chamber pressure, but within five cycles of pressure oscillation the chamber operates in a quasi-steady, albeit oscillatory manner.

REFERENCES

1. 성홍계, Vigor Yang, "램제트 엔진의 비정상 천이 유동에 관한 연구", 한국추진공학회지, 제4권 제1호, pp.74-92, 2000.
2. Metghalchi, M. and Keck, J. C., "Burning Velocities of Mixtures of Air with Methanol, Isooctane, and Indolene at High Pressure and Temperatures," Combustion and Flame, Vol. 48, pp. 191-210, 1982.
3. Klimov, A. M., "Premixed Turbulent Flames-Interplay of Hydrodynamic and Chemical Phenomena," Progress in Astronautics and Aeronautics, Vol. 88, pp. 133-146, 1983.
4. Bogar, T. J., Sajben, M., and Kroutil, J. C., "Characteristic Frequencies of Transonic Diffuser Flow Oscillations," AIAA Journal, Vol. 21, 1983, pp. 1232-1240.
5. White, F. M., "Fluid Mechanics," 2nd Ed., pp. 263, 1986, New York: McGraw-Hill.