An Experimental Investigation of the Supersonic Planar Mixing Layer with Finite Thickness

Hailong Zhang, Jiping Wu, Jian Chen, Weidong Liu*

Science and Technology on Scramjet Laboratory, National University of Defense Technology, ChangSha 410073, PR China

Abstract

Nanoparticle-based Planar Laser Scattering (NPLS) experiments were launched to get the fine structure of the supersonic planar mixing layer with finite thickness in the present study. Different from the turbulent development of supersonic planar mixing layer with thin thickness, the development of supersonic planar mixing layer with finite thickness is rapidly. The large-scale structures of mixing layer that possess the characters of quick movement and slow changes transmit to downriver at invariable speed. The transverse results show that the mixing layer is strip of right and dim and possess 3D characteristics. Results indicate that the higher the pressure of the high speed side, the thicker the mixing layer is. The development of mixing layer is restrained when the pressure of lower speed side is higher. The present study can make a contribution to the mixing enhancement.

© 2015 The Authors. Published by Elsevier Ltd.

Keywords: Supersonic mixing layer; NPLS; finite thickness; vortices

1. Introduction

Scramjet is prosperously investigated by all around the world because of its great performance in hypersonic flight condition. Supersonic reacting mixing layer is the typical flow structure in Scramjet. Although the structure is very simple, it contains almost all of the problems that relate to the chemistry and fluent. As this reason, it’s very important to understand the inner mechanism. Supersonic reacting mixing layer is absolutely mixed by fuel and air, so studying on the supersonic turbulent mixing is worthy.

* Corresponding author. Tel.: +86-13677354159
E-mail address: dragon.234@163.com
Mixing layer contains planar mixing layer and annular mixing layer geometrically. Two airstreams at different velocity flow through a strut is one of the typical flow structures [1]. This flow structure can produce vortices because of K-H instability. The question attracted many investigators’ attention during the last ten years. Experimental results of reacting and non-reacting [2,3] have been validated by simulation [4,5] in the condition of this structure. But among all the models, the thickness of the strut is very small and the instability of the recirculating flow is not intensity. But the mixing layer of DCR is the typical mixing layer that flow through clapboard with limited thickness.

Different from the development of the supersonic planar mixing layer with thin thickness, the mixing layer with finite thickness possesses more complex flow structure. Since the clapboard is not thin, the shear layers border a recirculation region immediately just behind it. The edge of the recirculation region is the adjacent flow. The development of large-scale structures of mixing layer relates to the instability of recirculation zone and recompression shock that behind the recirculation zone. The former studies [6,7] indicate that flame-holding depends on the recirculation zone behind the strut. Increase the thickness of the strut can enhance the mixing and stability of the flame. Someone had found that in the progress of the combustion of H₂/Air, the mixing condition decide the reacting. Different thickness of the strut affect the reacting directly [8,9]. But the thicker the strut is, the bigger total pressure loss increase. Therefore, it's very necessary to study on the supersonic mixing with finite thickness.

K.M.Smith [10] studies of the large-scale structure have suggested the thickness of the clapboard decides the development of the large-scale structure. Yan [11] and Yu [12] also find similar conclusions through simulation. But these studies mainly concentrate on simulation or the thickness of the clapboard is really small. That is to say, there is no fine evidence to support the conclusions.

NPLS experiments were launched to investigate supersonic mixing layer with finite thickness in order to explore the characteristics of the flow in the present study.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>height of trail thickness of nozzle</td>
</tr>
<tr>
<td>H</td>
<td>height of the experimental section</td>
</tr>
<tr>
<td>M₁</td>
<td>Mach number of upside</td>
</tr>
<tr>
<td>M₂</td>
<td>Mach number of downside</td>
</tr>
<tr>
<td>P₁</td>
<td>static pressure of upside</td>
</tr>
<tr>
<td>P₂</td>
<td>static pressure of downside</td>
</tr>
<tr>
<td>θ</td>
<td>momentum thickness</td>
</tr>
</tbody>
</table>

2. Experimental Techniques

2.1. Experimental Setup

All the experiments were operated in a supersonic suction type wind tunnel. A flat splitter is embedded along the center line from inlet of the tunnel to the beginning of the lava nozzle. Through change the standard of the nozzle to come true different experiments. The model consisted of a double Mach number nozzle terminated with a limited thickness trailing edge, shown as Fig.1. In order to investigate the characteristic of large-scale structures and effects of the geometrical structure and the pressure, NPLS experiments were launched. The conditions of the experiment show in Table.1.

In order to find the characteristics of the supersonic mixing layer with finite thickness, the development of the supersonic mixing layer with thin thickness are also discussed. By comparing the differences between the different conditions, some conclusions can be got. In the present study, four groups of experiments have been operated.
Fig. 1. Schematic of experimental model

Table 1. Conditions of supersonic planar mixing layer experiment

<table>
<thead>
<tr>
<th>Trail thickness of nozzle h (mm)</th>
<th>Mach number</th>
<th>Pressure matching condition</th>
<th>Temperature T (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_1$</td>
<td>$M_2$</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>$P_1 = P_2$</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1.5</td>
<td>$P_1 = P_2$</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.5</td>
<td>$P_1 &lt; P_2$</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1.5</td>
<td>$P_1 &gt; P_2$</td>
</tr>
</tbody>
</table>

Annotate: $M_1, M_2$ are up and down Mach number respectively, $P_1, P_2$ are up and down static-pressure respectively.

2.2. Experimental technology

Based on Rayleigh scattering, Zhao [13] et al ameliorated the technology to Nanoparticle-based Planar Laser Scattering (NPLS). In NPLS, nanoparticles and pulsed planar laser were used as tracer and illumination respectively. With the use of NPLS, complex flow structures including shock, boundary layer, oblique shock and mixing layer can be imaged at high signal-to-noise ratio and high spatiotemporal resolution. The system consists of a computer, a Charge Couple Device (CCD) camera, a synchronizer, a nanoparticle generator and a double-pulsed laser with pulse energy of 350mJ per 6ns and wavelength of 532nm.

Through change the pressure of the nanoparticle generator to control the density of the nanoparticle. Variation of the concentration of the nanoparticle can show the density of the flow by using the system and characteristics of the density fluctuation can be revealed.

3. Results

3.1. Experimental technology

Just as Fig. 2 shown, the development of the supersonic planar mixing layer with thin thickness can be divided as three parts including (1) laminar flow section, (2) transition section and (3) complete turbulent section. At the beginning, the laminar flow section is clear. In this section the main characteristic is molecular diffuse and velocity shear. With the development of the mixing layer, the instability of K-H and velocity shear led the vortices to roll up. In this section momentum exchange and K-H vortices are the main characteristics. When come into the complete turbulent section, vortices become to match and combine. As the results, the vortices break up and become abnormality.
Figure 3 shows 0-90mm NPLS visualization results of h=10mm. Different from the structure with thin thickness, the structure of supersonic planar mixing layer with finite thickness is more complex. Since the clapboard is not thin, the shear layers border a recirculation region immediately just behind it. The edge of the recirculation region is the adjacent flow. Because of the thickness of the clapboard, Re is very high. The flow change into turbulent immediately, the edge of the recirculation region shows itself turbulent. There are two shock waves at the end of the recirculation because of the recompression.

The reattachment point is distinguished as pentangle. With the spreading of the shock waves, the mixing layer become thick and the large-scale structures come up. At the same time, the shock waves bend because of the function of the large-scale structure. It is found that the K-H vortices don’t appear at the beginning of the mixing layer. Turbulent mixing makes the large-scale structure roll up faster and mixing layer increasing thicker. At the same time, the vortices break down very rapidly and form some clusters. This phenomenon can be clearly captured in the dashed rectangular region. The progress shows that the development of the large-scale structure possesses periodicity character.
Fig. 4 illustrates the transverse NPLS visualization results. It can be seen that the density of the recirculation region is small and the light and dim parts which respect high and low speed side respectively distributing like some strips at the center plane of the transverse. It can be concluded that the planar mixing layer with finite thickness possess 3D characteristic. That is to say, to find out the in-depth information, simulation on the supersonic mixing layer with finite thickness should be launched on the 3D model.

3.2. Characteristics of vortices

In order to investigate the periodicity character of the large-scale structures, the technic of span frame has been used to get the variety of the picture in a small time. Reasonable of choice for a time, the movement of the large-scale vortices can be captured between two pictures.

Fig. 5 shows the NPLS visualization results at the interval of 700ns. Three different location along stream wise shown as the circles in the picture has been studied. Partially enlarged details of vortices are shown too. The results show that the vortex in the circles moves 0.365m at the speed of 521.4m/s, 0.371m at the speed of 530m/s and 0.378m at the speed of 540m/s respectively. It seems that the large-scale vortices transmit to downriver at invariable speed. At the same time, the large-scale vortices don’t change essentially. That is to say the large-scale vortices possess the characters of quick movement and slow changes.
3.3. Discussion of Pressure Matching Condition

Compression is an important object to investigate the supersonic mixing layer. Different pressure matching conditions lead the instability of the vortices different and affect the mixing.

Fig. 6 shows the instantaneous NPLS visualization results of the different pressure-nonmatching extent. From the up to the down in the picture is the situation that the pressure of low speed side is higher, pressure matching, the pressure of the high speed side is high. It seems that the beginning part of the mixing layer is complete turbulent section. Pressure non-matching results in the strength and the span of the shock wave are different and affect the development of the large-scale structure finally. It can be concluded that the pressure non-matching is where the onset instability for the generation of the large-scale vortices. Based on the PIV averaged results which were captured by the same system, we adopt the momentum thickness which is defined as

\[
\theta = \int_{\infty}^{+\infty} \frac{\rho}{\rho_a} u^* (1 - u^*) dy
\]  

(3.1)

Where \( u^* = (u - u_a)(u_a - u_b) \), \( u_a \) \( u_b \) represent the speed of the upper and lower side respectively. The stream wise positions are normalized by the height \( H \) which is the height of the experimental section. The results, shown as Fig. 7, suggest that: the higher the pressure of the high speed side, the thicker the mixing layer is. The development of mixing layer is restrained when the pressure of lower speed side is higher. Besides, the large eddy is following the same trend.

4. Conclusion

NPLS experiments were launched to get the fine structure of the supersonic planar mixing layer with finite thickness in the present study. It can make a contribution to the mixing enhancement research. Based on the results, it can be concluded that:

1) Comparing with the mixing layer with thin thickness, the beginning part of the supersonic mixing layer with finite thickness is turbulent. The progress of the mixing is supersonic turbulent mixing.

2) The initial instability of the local place is stimulated by the compress shock wave which brought by the two different airstream at different velocity impact each other.
3) Compare the mixing efficiency of different pressure matching conditions by using momentum thickness. Results indicate that the higher the pressure of the high speed side is, the thicker the mixing layer is. The development of mixing layer is restrained when the pressure of lower speed side is higher. The development of mixing layer is restrained when the pressure of lower speed side is higher.

The present study can produce an evidence to support the former conclusions and make a contribution to the mixing enhancement and supply the initial data for the latter simulation study.

Acknowledgements

This work has been supported by the National Nature Science Foundation of China (Grant Nos.11172324 and 91116001).

References

[8] Lin, P. “Numerical simulation of a plane turbulent mixing layer with applications to isothermal Rapid reaction”. AIAA-87-1224