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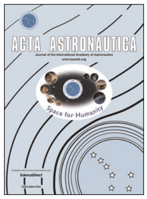

Investigation on flow and mixing characteristics of supersonic mixing layer induced by forced vibration of cantilever

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ABSTRACT

The mixing process has been an important issue for the design of supersonic combustion ramjet engine, and the mixing efficiency plays a crucial role in the improvement of the combustion efficiency. In the present study, nanoparticle-based planar laser scattering (NPLS), particle image velocimetry (PIV) and large eddy simulation (LES) are employed to investigate the flow and mixing characteristics of supersonic mixing layer under different forced vibration conditions. The indexes of fractal dimension, mixing layer thickness, momentum thickness and scalar mixing level are applied to describe the mixing process. Results show that different from the development and evolution of supersonic mixing layer without vibration, the flow under forced vibration is more likely to present the characteristics of three-dimensionality. The laminar flow region of mixing layer under forced vibration is greatly shortened and the scales of rolled up Kelvin–Helmholtz vortices become larger, which promote the mixing process remarkably. The fractal dimension distribution reveals that comparing with the flow without vibration, the turbulent fluctuation of supersonic mixing layer under forced vibration is more intense. Besides, the distribution of mixing layer thickness, momentum thickness and scalar mixing level are strongly influenced by forced vibration. Especially, when the forcing frequency is 4000 Hz, the mixing layer thickness and momentum thickness are 0.0391 m and 0.0222 m at the far field of 0.16 m, 83% and 131% higher than that without vibration at the same position, respectively.

1. Introduction

The development of supersonic aircraft has been one of the cutting edges in aerospace technology in recent years. As a key problem faced by the mission, the mixing of supersonic flow has been the focus of considerable research over the past three decades due to its importance in fundamental studies and practical applications. In many industrial applications, especially in the supersonic combustion ramjet engine (SCRAMJET) [1–3], most fundamental flow model simulating mixing in the scramjet combustor with parallel fuel injection is the 'compressible shear layer'. The dynamical behavior of the system is strongly affected by the mixing efficiency in a supersonic jet [4,5]. Thus, rapid mixing of two high-speed streams in a short distance is of great importance and it always receives a great deal of attention all over the world [6,7]. There are a lot of literatures that investigated the flow characteristics and mixing efficiency of supersonic mixing layer. To evaluate the compressibility level of mixing layer, convective Mach number (M_c) was proposed by Papamoschou et al. [8], their experimental study revealed that M_c had an important effect on the growth rate of mixing layer. Gutmark et al. [9] reported that with the increase of compressibility level, the

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growth rate and turbulence intensity of mixing layer are dramatically suppressed, which lead to poor mixing. By employing schlieren and PLIF techniques, Rossmann [10] found that with the increase of M_c, the thickness of mixing layer had strong reduction.

To control flow and promote mixing in supersonic condition, many techniques have been proposed during the past decades, including passive and active mixing enhancement techniques. Introducing additional three-dimensional perturbation into shear layer is generally considered as important passive methods, such as ramps, chevrons, tabs and so on [11,15–19]. These methods are beneficial to the mixing performance due to the generation of streamwise vortices, which increase the upper and lower streams contact surface. Callende et al. [16] proposed that by introducing chevrons to supersonic flow, the mixing efficiency was strongly enhanced, but suffered from aerodynamic and total pressure losses due to the squared of geometry of the chevrons. Besides, by adding forced excitation, such as Tollmien–Schlichting waves, electric spark excitation, active control techniques also play an important role in enhancing mixing efficiency [12–14,20–23]. These methods are valid because large scale structures can be induced through the excitation. The experiments done by McLaughlin et al. [22] revealed that an effective way to promote mixing was to utilize glow discharge excitation system in a supersonic mixing layer. In their experimental study, a high oscillating signal was passed through the copper electrode insulted from the aluminum trailing edge, which produced a glow between the copper and the aluminum when a threshold voltage was reached. This glow produced a very high temperature disturbance locally, slightly perturbing the flow adjacent to the electrodes.

However, among all these investigations, little has been done to capture the fine vortex structures of supersonic mixing layer to show the development and evolution of the flow fields. Meanwhile, the mechanisms of mixing enhancement in supersonic mixing layer under different control techniques are not fully understood. Apart from that, flow fields of supersonic mixing layer under vibration conditions have not been thoroughly researched and the physical mechanisms have not been fully understood as well, partly because of the complexity of fluid-structure interaction (FSI) [24,25]. Kim et al. [20] investigated the flow structures induced by the vibration of cantilever, the contours of velocity field were displayed with the Reynolds numbers of 101, 126 and 146, respectively. However, due to the equipment limitations, they could not get the characteristics of turbulent flow. By employing the ionic polymer of cantilever configuration, Williams et al. [21] investigated the mixing of microfluid, the results indicated that the mixing efficiency can be enhanced remarkably due to the influence of forced vibration. Likewise, because of the equipment limitations, the Reynolds number is only 10, and the flow investigated was laminar flow.

In the present study, to avoid the complicated process of flow control and mixing induced by FSI, forced vibration which decouples the FSI is applied to do the research in the supersonic mixing layer through a vibration shaker, and the forcing is achieved by vibrating a thin metal plate of cantilever configuration. The present work experimentally and numerically investigates the flow and mixing characteristics of supersonic mixing layer under forced vibration. First, to confirm the reliability of the numerical method, the comparisons of statistics between simulation and experiment are made. Then, the instantaneous transverse velocity distributions and the flow characteristics under different vibration conditions are analyzed in detail. Finally, by employing the indexes of fractal dimension, mixing layer thickness, momentum thickness and mixing layer level, the mixing efficiency under different vibration conditions are compared.

2. Experimental techniques

2.1. Experimental setup

A supersonic suction type wind tunnel is set up horizontally to carry out the experiments. To generate two free streams with different speeds at the test section, a flat splitter is embedded along the centerline from inlet of the wind tunnel to the beginning of the double nozzle. A total pressure controller is fitted at the front end of the stability section to regulate total pressure of low speed flow, which is to ensure static pressure matching at the nozzle exits. The wind tunnel has been well described in the former work [26] and the introduction of the tunnel will not be repeated here for brevity. In the present experiment, through calibrating the flow field, the flow parameters of supersonic mixing layer are listed in Table 1.

The schematic of the experimental arrangement is shown in Fig. 1(a). The thin metal plate (test model) is connected to the double-nozzle in a cantilevered manner with its leading edge clamped and trailing edge free. Through two rigid rod fixed at both sides of the trailing edge, the excitation is transmitted to the thin metal plate. Fig. 1(b) illustrates the schematic of streamwise section of the test model. The streamwise length of thin metal plate is 40 mm and the trailing edge thickness is 2 mm. The Cartesian coordinate system employed in the experiment is shown as well. *X*, *Y*, and *Z* denote the direction of streamwise, transverse and spanwise, respectively.

Table 1
Flow parameters of supersonic mixing layer.

Inlet no.	Inflow Mach number M_1, M_2	Convection Mach number M_c	Velocity (m s^{-1}) U_1, U_2	Total pressure (kPa) P_{o1}, P_{o2}	Static pressure (kPa) P_{s1}, P_{s2}	Total temperature (K) T_{o1},T_{o2}	Static temperature (K) T_{s1},T_{s2}
1	2.12	0.22	519	21.36	2.64	300	156
2	3.18		623	101.16	2.52	300	98