Aerospace Science and Technology 49 (2016) 250–258

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Mixing characteristics of vent slot mixer in supersonic flow

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ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 3 October 2015
Accepted 7 December 2015
Available online 14 December 2015

Keywords:
Vent slot mixer
Stereoscopic PIV
Counter-rotating vortex pair
Turbulent structure

ABSTRACT

Non-reacting experiments were performed to show the mixing characteristics of the vent slot mixer by the injector location in Mach 2 supersonic flow. As the injectant such as hydrogen, helium, and air was injected into the supersonic main flow, flow structures were visualized by schlieren photography and stereoscopic particle image velocimetry. Pressure measurement and gas sampling were conducted in order to compare with their flowfield visualization. The mixing performance is highly sensitive to the injection position of the vent slot mixer. While the injection occurs under the vent slot mixer, the remnant injectant is evenly distributed toward the spanwise direction. In the meantime, the injection behind the vent slot mixer generates the jet plume containing a counter-rotating vortex pair which mainly affects the velocity field and turbulent motion around the jet plume. In the case of the vent slot mixer, because the jet plume is combined with the nearby shear layer, the injectant in the jet plume can be supplied into the nearby shear layer.

1. Introduction

The supersonic combustion engine is a key to design hypersonic vehicle such as scramjet (supersonic combustion ramjet) engine and RBCC (Rocket Based Combined Cycle) engine [1–3]. However, it is believed to be very difficult to develop the supersonic combustion engine. The residence time of the fuel injectant is very short, resulting in not being well-mixed and not surely-ignited in the supersonic flow. Due to such difficulties, various mixing methods have been proposed during the last few decades [4]. Among them, transverse injection from a flat plate has the simplest configuration and induces an aerodynamic barrier, which is a bow shock, to give a chance of mixing fuel and air in the jet plume [5,6].

With the transverse injection, physical mixer models installed in the supersonic flow can enhance the mixing performance. Typically, step mixers have been extensively studied with an objective of extending the residence time of the fuel–air mixture with the simple configuration [7–9]. Upstream boundary layer is separated at the edge of the step mixer, creating the recirculation region behind the step mixer. If the fuel is injected in the recirculation region, the injectant can be sustained and slightly mixed in the recirculation region. However, because the step mixer indicates poor mass transfer in the recirculation region [8], a stirring device is required to mix the fuel–air mixture at macro- and micro-levels in the recirculation region. For example, Helmholtz resonators [10] generate an acoustic oscillation and hyper mixers [11–13] composed of wedges and ramps produce streamwise vortices by pressure gradient.

Based on these considerations, a new mixer model, vent slot mixer, was suggested in a previous work [14]. The step mixer was used to create a recirculation region which was augmented by adding an extended roof-plate at upper region of the step mixer. With the "well mixed" model [15], an active method for supplying air into the fuel–air mixing region was suggested by using a slot on the roof-plate. The main flow is considered to be entrained into the recirculation region through the slot due to the pressure gradient between the main flow and the recirculation region. Furthermore, the interaction of the inflow air in the recirculation region tends to induce some turbulent flow structures. This kind of the flow mechanism by the vent slot mixer was simulated with CFD (Computational Fluid Dynamics) analysis [14]. The inflow air through the slot into the recirculation region generated complex flow structures such as circulation bubbles and large-scale vortex structures. In addition, due to the inflow air interaction, the shear layer was gently extended and oscillated, increasing the mass transfer through the shear layer.

While the fuel was normally injected toward the roof-plate in the recirculation region, it was scattered near the roof-plate. Some fuel was intruded into the main flow and others were widely dispersed downstream in the recirculation region. Needless to say, it is important that the injector location is placed in the recirculation region because the fuel remnant in the recirculation is

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http://dx.doi.org/10.1016/j.ast.2015.12.011
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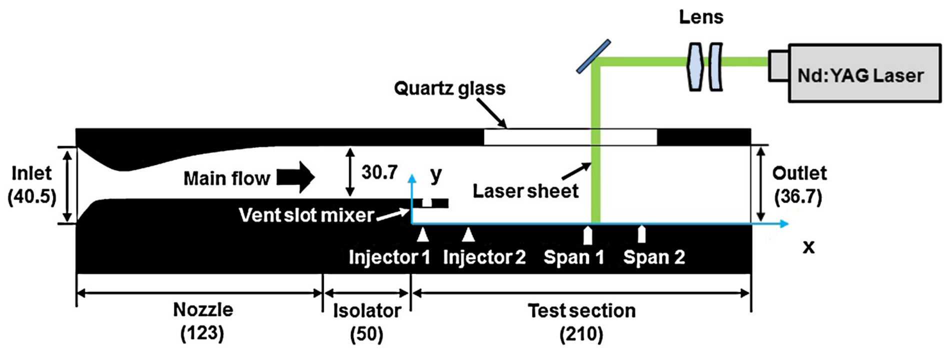

Fig. 1. Schematic diagram of laboratory-scaled supersonic wind tunnel.

dependent on the injector position [16]. For such considerations, in this study, an injector was additionally mounted at a place which would be less affected by the vent slot mixer to compare with the mixing characteristics of the previous experiment with respect to the injector location. In addition, turbulent parameters influencing the micro-scale mixing performance were investigated using a stereoscopic-PIV (particle image velocimetry) method.

2. Experimental setup

A laboratory-scaled supersonic wind-tunnel is presented in Fig. 1. A suction-type supersonic wind-tunnel was attached to the vacuum tank of 8 m^3. It is composed of a nozzle part, an isolator part and a test section. In this experimental study, non-reacting experiments were conducted to study mixing characteristics of a new mixer model compared with other mixer models [9,13]. Atmospheric air ($P_0 = 100$ kPa, $T_0 = 286$ K) in the laboratory was inhaled and accelerated through a Mach 2 half nozzle. Several mixer models, injection ports, a plasma torch, and pressure ports were embedded in the lower wall. The isolator was a rectangular duct of 50 mm long, 30.7 mm high and 30 mm wide, and the test section was 210 mm long by 36.7 mm high with the same width. The unit Reynolds number at the mixer model was approximately 6.6×10^5 m. The side windows were comprised of Pyrex® glass and a Quartz window was used in the upper wall in order to pass the laser sheet.

Two mixer models were used; one was a reference model (the step mixer) and the other was the vent slot mixer [14]. The vent slot mixer had 2 mm wide slot in the middle of the roof-plate, 2 mm thick by 6 mm long, extended from the step mixer of 6 mm height.

To discern the difference of the mixing and the flow structure according to the injector location, two injection ports were located at 2 mm (injector 1) and 9 mm (injector 2) from the step wall, respectively.

Pressure measurement and gas sampling were conducted through two port arrays which existed separately at 22 mm (span 1) and 30 mm (span 2) downstream from the step wall as shown in Fig. 2. Each port array had five holes with 5 mm interval. The wall pressure and the injection pressure were acquired using strain-gauge type pressure transducers, PDCR23D-200 psi (Scanivalve, Inc.) with ±1% accuracy and PABA200KP (Kyowa, Inc.) with ±2% accuracy, respectively. From the same port arrays, the gas was sampled using tubes of 2 mm diameter for 10 s, and then stored in small vacuum bottles. The sampled gas was examined with the gas chromatograph (CP-4900 Micro-GC: Varian, Inc.). The calculated uncertainty was less than 1% for N_2 and 6% for O_2 and H_2.

Schlieren and stereoscopic-PIV techniques were utilized to visualize the flow structures. For the schlieren method, the light source was a stroboscope lamp of 180 ns pulse time and the images were captured by a digital camera, Cannon EOS-D30.

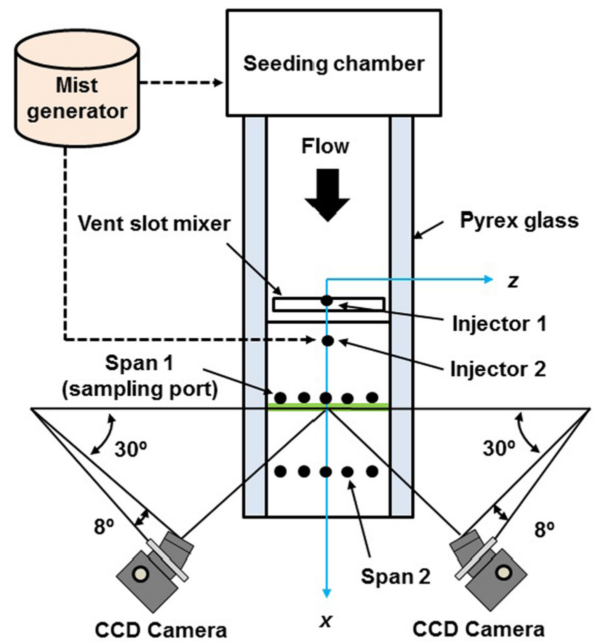

Fig. 2. Experimental measurement systems.

The stereoscopic-PIV system in Fig. 2 was available by the Scheimpflug condition [17] to view clear velocity fields and turbulent structures in the y–z cross-plane. Our previous studies have demonstrated calibration works about the stereoscopic-PIV system in detail [13,18,19]. The light source was a double-pulsed Nd:YAG laser (532 nm; 12 mJ pulse; pulse width 5–7 ns; Y12-15E: TSI, Inc.), which was modified to a laser sheet of 1.5 mm thick and 50 mm wide through cylindrical lenses. A pulse generator was used to synchronize the laser signals with two CCD (charge-coupled device) cameras (1600 × 1200 pixels; 28.77 μm square pixels resolution) with a Scheimpflug lens mount of Nikon PC-Micro 85 mm − $f/2.8$ lens. The interrogation window size was 33 × 33 pixels. Each tilt angle of the CCD cameras relative to the image plane was 30 degrees and the Scheimpflug lens mount was adjusted angularly to clear the images. The commercial software FtrPIV (Flowtech Research, Inc.) controlled the whole arrangement about the stereoscopic-PIV measurement. Droplets of dioctyl-sebacate (density 913.5 kg/m^3) were added to working gas (air) by the Laskin nozzle; the mean diameter of the trace particles was of 1 μm [20].

With the correction method [19] based on the Basset–Boussinesq–Oseen equation [21], the Stokes drag coefficient was evaluated to confirm the flow tracer fidelity of the particle in the supersonic flow. In previous researches [19,20], the order of the Stokes number was approximately 10^{-1} for the normal injection in the