Mean and turbulent velocity measurements of supersonic mixing layers*

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Abstract. The behavior of supersonic mixing layers under three conditions has been examined by schlieren photography and laser Doppler velocimetry. In the schlieren photographs, some large-scale, repetitive patterns were observed within the mixing layer; however, these structures do not appear to dominate the mixing layer character under the present flow conditions. It was found that higher levels of secondary freestream turbulence did not increase the peak turbulence intensity observed within the mixing layer, but slightly increased the growth rate. Higher levels of freestream turbulence also reduced the axial distance required for development of the mean velocity. At higher convective Mach numbers, the mixing layer growth rate was found to be smaller than that of an incompressible mixing layer at the same velocity and freestream density ratio. The increase in convective Mach number also caused a decrease in the turbulence intensity ($\sigma_u/\Delta U$).

List of symbols

- speed of sound
- total mixing layer thickness between $U_1 - 0.1 \Delta U$ and $U_2 + 0.1 \Delta U$
- normalized third moment of $u$-velocity, $f = \langle u'^3 \rangle / (\Delta U)^3$
- normalized triple product of $u'^2 v'$, $g = \langle u'^2 v' \rangle / (\Delta U)^3$
- normalized triple product of $u' v'^2$, $h = \langle u' v'^2 \rangle / (\Delta U)^3$
- axial distance for similarity in the mean velocity
- axial distance for similarity in the turbulence intensity
- convective Mach number (for $\gamma_1 = \gamma_2$), $M_c = (U_1 - U_2)/(a_1 + a_2)$
- static pressure
- freestream velocity ratio, $r = U_2/U_1$
- unit Reynolds number, $Re = \rho U/\mu$
- freestream density ratio, $\delta = \rho_2/\rho_1$
- total temperature
- instantaneous streamwise velocity
- deviation of $u$-velocity, $u' = u - U$
- local mean streamwise velocity
- primary freestream velocity
- secondary freestream velocity
- average of freestream velocities, $\bar{U} = (U_1 + U_2)/2$
- freestream velocity difference, $\Delta U = U_1 - U_2$
- instantaneous transverse velocity
- deviation of $v$-velocity, $v' = v - \bar{V}$
- local mean transverse velocity

1 Introduction

Supersonic mixing layers are encountered within many practical devices such as supersonic ejectors for pumping and entrainment applications and in many scramjet engine designs for hypersonic vehicles. In addition, the performance of these devices is critically dependent upon the turbulent mixing behavior of these compressible mixing layers. Thus, the overriding goal of this work is to determine the mean and turbulent fluid dynamic mechanisms occurring in supersonic mixing layers.

The behavior of subsonic mixing layers has been studied extensively by several researchers (e.g., Wygnanski and Fiedler 1970; Brown and Roshko 1974; Batt 1977) and is therefore much better understood than that of supersonic mixing layers. Wygnanski and Fiedler (1970) have provided detailed mean and turbulent velocity measurements of subsonic mixing layers. Less research has been conducted on supersonic mixing layers; however, it is known that the growth rate of supersonic mixing layers is smaller than that of subsonic mixing layers at the same velocity and density ratios. Brown and Roshko (1974), in addition to observing large-scale structures within turbulent incompressible mix-
ing layers, have shown that the reduction in growth rate of supersonic mixing layers could not be explained solely by density ratio effects as had previously been implied. The convective Mach number, a Mach number of the freestream flows with respect to a frame of reference moving at the convective velocity of the mixing layer, has been proposed by Bogdanoff (1983) as a significant parameter for evaluating the compressibility of supersonic mixing layers. A correlation between the convective Mach number and the ratio of compressible to incompressible mixing layer growth rates at the same velocity and density ratios is supported by the work of Chinzei et al. (1986) and Papamoschou (1986). However, previous work on supersonic mixing layers has concentrated primarily on mean growth rates; little is known about the turbulence behavior of supersonic mixing layers and how it is affected by various parameters. The present research, as well as the recent investigations of Samimy and Elliott (1988), have begun to address this issue.

The specific objectives of this work are to examine the effects of freestream turbulence and convective Mach number on the mean and turbulent velocity fields of supersonic mixing layers. This has been accomplished through the use of schlieren photography and two-component, coincident laser Doppler velocimetry.

2 Experimental facilities

The wind-tunnel employed in these experiments produces a two-stream mixing layer where, for the current studies, both streams were supersonic (Mach numbers of about 2.0 and 1.4). The facility has the capacity to independently heat each air stream (to a maximum temperature of approximately 900 K), thereby allowing variation of the velocity ratio, density ratio and convective Mach number of the mixing layer. Flow conditioning screens and honeycomb, as well as total pressure and total temperature probes for display and feedback to the system control valves, are located in the plenum chambers preceding the converging-diverging nozzle in each stream (Fig. 1). The nozzles have been designed by the method of characteristics (Carroll et al. 1986) to produce uniform flow at their exits. The two streams are brought together at an angle of 2.5° across a thin splitter plate with a tip height of approximately 0.5 mm. Each stream has an exit height of 23.75 mm and a width of 95 mm. The divergence angle of the upper and lower walls of the test section is adjustable to allow for control of the streamwise pressure gradient. Both sidewalls of the test section have windows which can be mounted in two streamwise locations to give a total viewing length of about 500 mm. This optical access is necessary for schlieren photography and laser Doppler velocimetry (LDV) measurements. A pressure tap sidewall blank can also be mounted in place of one of the window frames and an electronic pressure scanner can be used to measure the mixing layer static pressure distribution to verify that the upper and lower wall divergence provides the desired axial pressure gradient. Under the current operating conditions and with the available air supply, the wind-tunnel has a run time of approximately six minutes. For more details on the test section, see Messersmith et al. (1987).

A conventional Toeppler schlieren system has been applied to observe the basic mixing layer flow structure. A Xenon spark light source (20 ns pulse duration) is used to "freeze" the flow. Lenses are utilized for collimating the light, and three overlapping photographs are required to cover the length of each window. The knife edge is positioned horizontally. Kodak T-Max 400 film is used in a 35 mm format camera with a macro lens, and is processed by normal development.

A two-color, two-component, dual-beam LDV system has been employed to measure the mixing layer velocity field. The collection optics are placed at approximately 10° off the forward scatter axis. The effective measurement volume diameter and length to the e-2 intensity level are approximately 0.12 and 1.6 mm, respectively. Optical fibers are used to transmit the laser beams to a probe which (along with the receiving optics) resides on a three-dimensional traversing table that allows location of the measurement volume to an accuracy of within ±2.5 μm per 25 mm of travel. Frequency counters are employed with the two-channel coincidence window set at 1 μs. Fluidized beds seed both streams with TiO2 particles having an average diameter of 0.4 μm (Agarwal and Johnson 1981). The level of seeding of each stream is adjusted to produce the same LDV data rate (about 1,000 samples per s) in both freestreams. The effects of particle concentration biasing will be discussed below.

At each measurement location, at least 2,000 instantaneous velocity samples were taken. The data was not modified by any velocity debiasing scheme since such modifications would be very small (less than 2%) for the measurements of this study where the local turbulence intensity (Ct/U) was always less than 14% (Petrie et al. 1988). Also, no correction was made for fringe biasing since the measured instantaneous flow angle never exceeded ±18° from the freestream direction, with the corresponding two channel