Investigation of Supersonic Mixing Layers

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Abstract

A NEWLY constructed, dual-stream, supersonic wind tunnel has been designed to provide comparatively long run times for investigations of reactive and nonreactive, two-dimensional supersonic mixing layers. Control of the stagnation temperatures enables the velocity ratio, density ratio, and convective Mach number of the two streams to be varied. Laser Doppler velocimetry has been employed to measure the incoming boundary layers, the subsequent compressible mixing-layer growth rate, and the mean and turbulent velocity field development for two density ratios of 0.76 and 1.56, corresponding to velocity ratios of 0.79 and 0.58 and convective Mach numbers of 0.20 and 0.45, respectively. For a given density and velocity ratio, the convective Mach number has been found to correlate the ratio of compressible to incompressible mixing layer growth rate, as suggested by other workers.

Contents

The characteristics of reactive, compressible mixing layers will play an important role in the design and development of engines for use in a hypersonic vehicle. The mechanisms governing the so called "compressibility" effect,[1-3] the general trend of reduced growth rates of compressible mixing layers with increased convective Mach number, must be better understood if reactive supersonic mixing layers are to provide an efficient means of combustion. A new wind tunnel has been designed to investigate both reactive and nonreactive, supersonic mixing layers. The flow facility[4] is a planar, two-dimensional, dual-stream arrangement with mixing downstream of a thin-edged splitter plate. A large bank of compressed air tanks and a heat exchanger enable the facility to produce variations in the density and velocity ratios, thereby indirectly varying the compressibility effect through control of the stagnation temperatures of the two streams.

The design of the new dual-stream supersonic mixing/combustion laboratory was dependent upon existing equipment. Available facilities include a natural gas-fired, nonvitiated heat exchanger in line with an integrated system of compressed air tanks fed by two air compressors, one an Ingersoll-Rand compressor that can deliver 0.75 kg/s of air at 860 kPa while the other, a Gardner-Denver compresser, supplements the system with an additional 0.4 kg/s at tank pressures below 690 kPa. The heat exchanger can provide air at a maximum temperature of 900 K for mass flow rates up to 2.25 kg/s. Figure 1 is a schematic of the test section. The dual-stream system is required to be large enough to minimize wall effects and to permit access for optical diagnostics yet not so large as to deplete the capacity of the air supply system too quickly. The test section is 95 mm wide by 47.5 mm high at the tip of the splitter plate. The exit height of the primary (higher Mach number) stream is 23.75 mm, and the secondary (lower Mach number) stream has an exit height of 23.25 mm. Thus, the splitter plate tip has a finite thickness of 0.5 mm.

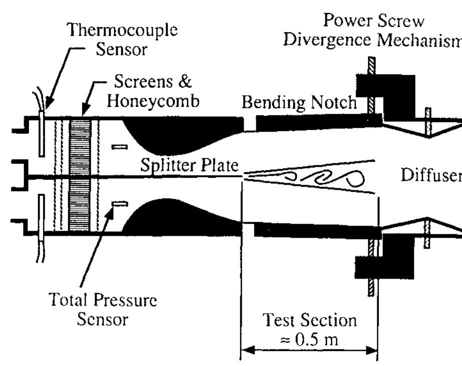

Fig. 1 Schematic of supersonic shear-layer facility (not to scale).

The supersonic nozzle blocks were designed to generate plane, uniform flow using a method of characteristics code iteratively with a compressible boundary-layer code to account for the boundary-layer displacement thickness of the nozzle flow. Laser Doppler velocimetry has been used to measure the boundary-layer thicknesses, which are 2.4 and 2.7 mm for the primary and secondary streams in cold flow, respectively. The splitter plate separating the incoming streams has a relative flow angle of 2.5 deg. The nozzle blocks, which also continue downstream as the upper and lower walls of the test section, are notched and attached to a power screw divergence mechanism downstream. This allows the wall divergence to be adjusted to control the pressure gradient in the mixing layer. The divergence angle is chosen to minimize the streamwise pressure gradient. A PSI (pressure systems incorporated) electronic pressure scanning device is used to monitor the pressure in the mixing layer at several streamwise locations. Optical access to the test section is provided for approximately 0.5 m downstream of the splitter plate tip.

Several nonintrusive, optical diagnostic techniques are being utilized in the current study of reactive and nonreactive, supersonic mixing layers. These range from traditional schlieren flow visualization to more sophisticated laser-based techniques: laser Doppler velocimetry (LDV), laser-induced fluorescence (LIF), and Mie and Rayleigh scattering. Flow visualizations using black and white schlieren photography have been very successful. The basic system consists of a 20-ns pulse duration xenon flash lamp and 150-mm-diam f/6.67 collimating/decollimating lenses.

Mean velocity mappings and turbulence quantities are measured with an LDV system. The thermal systems incorporated (TSI), two-color, two-component LDV system utilizes the blue (488-nm) and the green (514.5-nm) lines of a 4-W Cooper Lasersonics (Lexel) argon ion laser. Since particle seeders which could handle the high pressures of the air supply system were not commercially available, fluidized-bed seeders were constructed. The seeders are designed to introduce 0.4-

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Table 1 Experimental operating conditions

Flow condition	Cold/cold	Hot/cold
$M_{primary}$	2.04	1.91
$M_{secondary}$	1.40	1.37
$U_{primary}$(m/s)	519	700
$U_{secondary}$(m/s)	409	403
$T_{0,primary}$(K)	295	578
$T_{0,secondary}$(K)	295	295
$P_{average}$(kPa)	46.2	49.0
Re_p ($\times$ 10^7 m^{-1})	4.7	1.8
Re_s ($\times$ 10^7 m^{-1})	2.2	2.3
$M_{convective}$	0.20	0.45
$\lambda_u = U_s/U_p$	0.79	0.58
$\lambda_p = \rho_s/\rho_p$	0.76	1.56
δ_c	0.021	0.045

μm average diameter titanium dioxide (TiO_2) particles into the air supply lines in a steady, controllable manner.

Table 1 depicts the pertinent operating parameters for two test flow conditions conducted to date. The first case, referred to as the cold/cold scenario was for cold flow in both streams, which resulted in a density ratio of 0.76 and a velocity ratio of 0.79 due to the expansions in the separate nozzles. This gave a convective Mach number of 0.20. A second case, referred to as the hot/cold scenario, was for hot flow in the primary stream and cold flow in the secondary stream (density ratio of 1.56 and velocity ratio of 0.58). A higher convective Mach number of 0.45 was achieved under these conditions.

Although shock and expansion waves originate at the tip of the splitter plate and reflect through the test section, a static pressure trace the length of the test section suggests that the pressure is nearly constant. Transverse velocity profiles were measured using the LDV system at several streamwise locations from the tip of the splitter plate. The extent of the mixing layer is defined as the transverse locations where $U = U_p - 0.1\Delta U$ and $U = U_s + 0.1\Delta U$, respectively. The slope of these transverse locations with axial distance in the fully developed region was used to accurately establish the compressible mixing layer growth rate δ_c'.

With regard to the convective Mach number concept, the experimental compressible mixing-layer growth rates for both

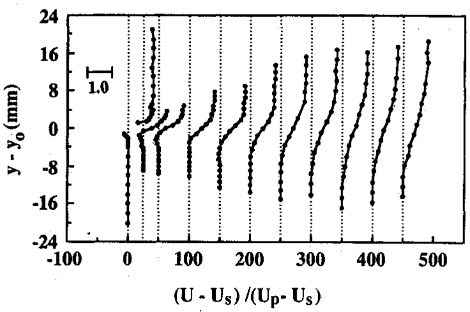

Fig. 2 Normalized velocity profile development for the hot/cold case.

test flow scenarios have been normalized to the relevant incompressible growth rate and plotted with other experimental data.[3,5-7] The observed mixing-layer growth rates are in good agreement with the trends of the previous data. Little or no compressibility effect was observed for the cold/cold scenario ($M_c = 0.20$), and only slight compressibility was observed for the hot/cold scenario ($M_c = 0.45$) as expected. Figure 2 presents a typical example of the normalized velocity profile development measured for the hot/cold case.

Future studies will focus on the combustion of a fuel-rich, lower Mach number stream mixing with an oxidizing higher Mach number stream. To create a fuel-rich stream in the laboratory, a "gas generator" has been incorporated into the flow facility. The gas generator will serve both as a vitiated heat exchanger, which effectively extends the range of the existing heat exchanger and serves as a source of excess fuel in the hot, lower Mach number stream. Design and construction of the gas generator, employing a high air-flow capacity burner installed in line upstream of the plenum chambers, has been completed. Hydrocarbon fuels such as propane or natural gas can be used. The combustion chamber of the gas generator is fabricated out of a ceramic insulated, high-temperature alloy pipe, and the excess fuel, required to complete combustion and to render the stream fuel-rich for subsequent combustion in the mixing layer, is injected coaxially with the burner flame.

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