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Test Gas Vitiation Effects in a Dual-Mode Scramjet Combustor

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An experimental study was conducted to characterize the influence of combustion air preheater major vitiate species (H_2O and CO_2) on scramjet combustion. These species were added to an initially clean airflow that was supplied by an electrically heated facility. With dry air, the scramjet combustor operated in the supersonic mode at an equivalence ratio in the range of 0.25–0.32 and transitioned to dual mode over an equivalence ratio range of 0.35–0.37. At an equivalence ratio of 0.27, the combustor operated in the supersonic mode for three cases: 1) dry air, 2) air vitiated with 5% H_2O by mole, and 3) air vitiated with 5% H_2O and 2.5% CO_2 by mole. In the second case, the combustor pressure distribution decreased 10% relative to dry air and, in the third case, another 2% decrease was measured. At an equivalence ratio of 0.35, the combustor operated in the dual mode with dry air, but in the supersonic mode with 7% H_2O. This is the first demonstration of mode transition solely caused by test gas vitiation. It is therefore important to account for such effects when extrapolating from vitiated ground testing to flight.

I. Introduction

THE development of propulsion systems for hypersonic flight must rely heavily on ground testing for screening and validation of engine concepts. Information gained during the ground testing may also be used to validate computational fluid dynamics (CFD) codes for extending the flight envelope to conditions not achievable in ground test facilities. To conduct meaningful tests on subscale engines and engine components on the ground, the facilities must supply a test gas with properties representative of those of flight conditions. For example, the Mach number, total and static conditions at the entrance to a combustor with specified inlet compression have been published [1].

Generation of the high enthalpies required to simulate hypersonic flight conditions relies on one of five methods of air heating: 1) shock tube heating, 2) storage heating, 3) arc heating, 4) combustion heating, or 5) electric heating. There are advantages to each type of heating. Shock tubes provide the highest enthalpy, but have test times of the order of milliseconds. Storage heaters, such as pebble beds, provide time-dependent total conditions and also can contaminate the test gas with particulates. Arc and combustion heaters can provide long test times, but also introduce contaminating species into the test gas. Arc heaters produce oxides of nitrogen in concentrations as high as 3.5 mol percent [2]. A combustion heater (i. e., vitiated heater) produces mole fractions of up to 30 mol percent of water when hydrogen is burned, with additional oxides of carbon when hydrocarbon fuel is used. In addition, the combustion-heated test gas contains nonequilibrium concentrations of radical species (H, O, OH, and NO), which can have a major effect on the kinetics of hydrogen/air combustion [3]. Electric heating produces a clean test gas, but is currently somewhat limited in achievable maximum total enthalpy.

Based on operating cost and ease of operation, combustion air preheating is the most widely used method of obtaining high enthalpy air up to a Mach 8 simulation, resulting in air that will include significant fractions of H_2O or H_2O and CO_2. The study reported herein focuses on the effects of these freestream major species contaminants on the dual-mode combustion of hydrogen in air of a scramjet combustor. The large concentrations of water vapor in vitiated air will affect the bulk thermodynamic properties of the test gas (i.e., specific heat and mean molecular weight) as well as change the reaction kinetics. Changing the bulk thermodynamic properties through vitiation has been shown to lower the internal thrust generated in a scramjet engine owing to a reduction in the mass flow captured (lower molecular weight) and lower the combustion-generated temperature rise due to combustion (higher specific heat) [4]. The addition of water vapor also significantly increases the ignition delay time of hydrogen in air at static temperatures near the auto ignition temperature of about 1000 K. This increase has been calculated to be 1–2 orders of magnitude at 1000 K as the water concentration is increased from 0 to 10% [5]. This lengthening of the ignition delay time is due to the increased third body efficiency of water relative to nitrogen or oxygen (15 times greater) in the chain terminating reaction that produces HO_2. HO_2 is a relatively unreactive species that forms through the reaction $H + O_2 + M \rightarrow HO_2 + M$, where M is a third body molecule. This reaction depletes available H atoms from chain branching reactions, such as $H + O_2 \rightarrow OH + O$, and because OH is an important radical in the formation of water, the ignition delay of the hydrogen oxidation process is lengthened. Whereas the ignition delay time is increased, the effect of water vapor on the reaction time (the time from the onset of ignition to 95% of the equilibrium temperature rise) has been calculated to be negligible [3].

The addition of carbon dioxide affects the bulk thermodynamic properties primarily through its higher molecular weight relative to air. Carbon dioxide is predicted to have a similar effect on the ignition delay as water vapor, increasing the delay at static temperatures near 1000 K. However, the effect is weaker than for water vapor because the third body efficiency of carbon dioxide is only about 23% of that of water vapor in the chain terminating reaction [5]. In addition, mole fractions of carbon dioxide are typically one-half that of water vapor when a hydrocarbon fuel is used for combustion preheating.

Few experiments have been conducted on the effects of water vapor or carbon dioxide on hydrogen–air combustion. The addition of steam to premixed hydrogen–air mixtures has been shown to noticeably decrease the laminar burning velocity [6], although later results showed the opposite effect [7]. The addition of water to opposed jet hydrogen–air diffusion flames has been shown to decrease the hydrogen mass flux at blowoff by 10% relative to clean air [8]. Although these experimental results are not consistent, they

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do show that the effect of water vapor at a level around 10% does have an important effect on combustion in both premixed and diffusion flames.

A direct comparison was made of scramjet engine performance at Mach 6 enthalpy by operating an engine supplied with inlet air heated by a combustion air preheater and with air heated using a storage heater [9]. In these tests the influence of major and minor species contaminants could not be separated, because a combustion heater produces both, and includes a considerable uncertainty in the level of minor species. However, significant differences in performance between dry and vitiated air were observed. Relative to clean air, the engine self ignited with vitiated air, but not with clean air. This was attributed to combustion-generated radicals in the inlet air present in the vitiated air case but not in the clean. Thermal choking occurred at lower fueling rates with dry air; consequently, higher performance was measured using vitiated air. As a follow-up to the experiments of Mitani et al. [9], the performance of a scramjet combustor in a flow supplied by a combustion air preheater was compared with that for a flow supplied by a shock tunnel [10]. The pressure measurements in the combustor for the shock tunnel were found to be up to 15% higher than for the combustion air preheater experiment. The differences were not only attributed to flow vitiates of the combustion heater, but also to other differences in the combustor inlet conditions, such as boundary layers, and hence, the effects of flow vitiates could not be fully isolated.

The reliance on combustion air preheating for supplying high enthalpy air for hypersonic air-breathing engine testing requires an understanding of the impact of the altered inlet air composition on engine performance. Issues related to major species contamination include both kinetic and physical effects. At low concentrations, minor species effects are more related to kinetics. Understanding the complex issues and the impact on hypersonic combustion test results requires a systematic evaluation in sets of well-controlled experiments accompanied by modeling support. This study examines the influence of water and carbon dioxide vitiation on the performance of a model dual-mode scramjet and is aimed at contributing to this understanding. The manuscript begins with a description of the clean-air supersonic combustion facility that was used for the experiments, together with a description of the dual-mode scramjet combustor. The performance of the combustor in nonvitiated air is first fully characterized before examining the effects of freestream vitiation

II. Supersonic Combustion Test Facility

The University of Virginia Supersonic Combustion Facility is designed to provide a high-enthalpy, dry, oil-free, and clean flow of continuous air to a test section at pressures to 1 atm static at Mach 2 or 0.5 atm static at Mach 3. The vertically mounted facility, shown in Fig. 1, is capable of providing a total temperature of 1200 K. Facility design considerations have been published previously [11]. The heater is mounted in a pit below floor level with the nozzle and test section above floor level for easy access to optical diagnostics. Inlet air to the heater vessel enters the top of the vessel where it flows downward through an annulus. At the bottom of the vessel, the flow enters the inner heater core.

Air heating is accomplished using resistive heating elements. At present, 14 heating modules are installed, providing the total temperature of 1200 K. An additional heater provides H_2 fuel heating to 500 K. (It was subsequently found that heating the fuel to this level had no measurable effect on the combustion.) The method of air heating and continuous operation permit straightforward control of critical flow and combustion-related parameters, including inlet air total temperature and pressure and fuel total temperature and pressure. Steady state is also achieved on boundary temperatures and heat transfer rates. Typical air total temperature, following warmup, is maintained to within 3 K and fuel temperature to within 2 K. Tunnel warmup typically was accomplished during a 2 h period (to avoid thermal shock to the heater) and cooldown for about 1 h. Tunnel run times were typically several hours, limited only by the amount of stored hydrogen fuel. Operating characteristics of the facility have been published previously [12].

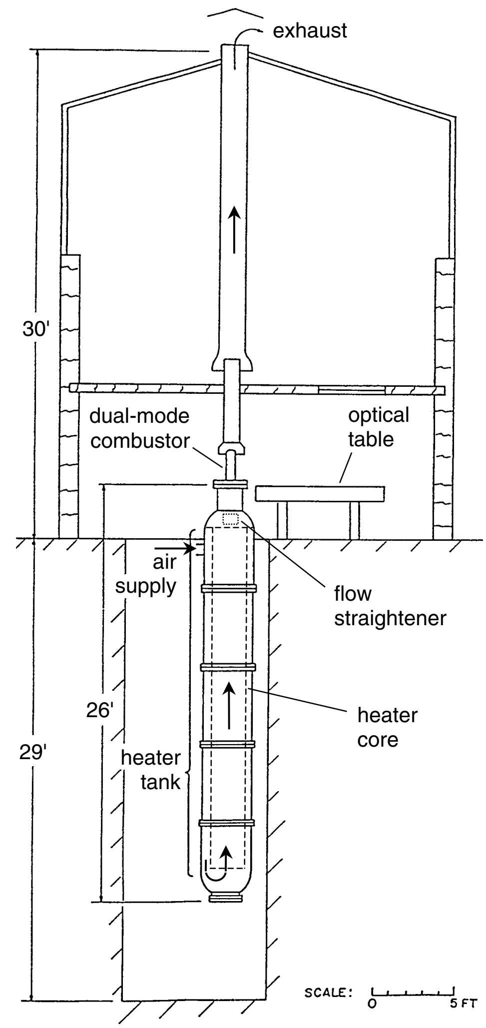

Fig. 1 Schematic of University of Virginia Supersonic Combustion Facility.

The simulation of a combustion-heated, high-enthalpy facility, required the addition of H_2O, in the form of steam, as well as CO_2 and O_2 (to maintain a mole fraction of 21%) to match contaminants present in a vitiated flow. CO_2 and O_2 were added to the inlet air where the air enters the heater tank (see Fig. 1) and was well mixed before entering the heater core. Several alternatives existed for injection of steam. For steam partial pressures limited by saturation at the inlet air temperature, steam injection at the heater core inlet to levels of 5 mol percent could be achieved without condensation. This steam concentration level was somewhat less than would be introduced by a combustion air preheater heating air to 1200 K. A full simulation of vitiates in air heated to 1200 K would include approximately 13 mol percent of H_2O for a hydrogen-fueled preheater and approximately 7 and 3.5 mol percents of H_2O and CO_2, respectively, for a CH_4-fueled preheater. Steam injection to 7 mol percent was accomplished in the present study by incorporating steam heating through tracer lines on the outside of the heater tank vessel and elevating the inlet air temperature to above the saturation temperature. A high-pressure steam generator delivering up to 278 kg/h of steam was installed for the contaminant studies. The steam was delivered to the airflow through a series of nozzles designed to ensure that mixing was completed over the length of the heater core.

Reacting flow experiments were conducted using an unswept ramp with hydrogen fuel injection from the ramp base. Figure 2 shows a schematic of the test section. The ramp height H was 0.64 cm and is used to normalize all dimensions. Inlet Mach 2 air entered the $4H \times 6H$ combustion test section upstream of a 10-deg unswept compression ramp of aspect ratio 2 (width $= 2H$). Hydrogen was

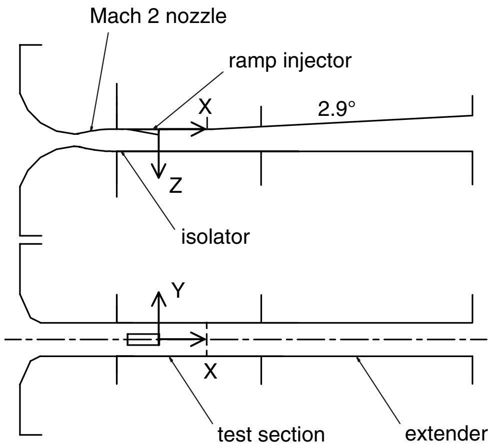

Fig. 2 Schematic of dual-mode scramjet combustor (divergent extender configuration).

injected at Mach 1.7, normal to the ramp base. Streamwise vortices generated by the compression ramp provide effective fuel/air mixing. To facilitate flameholding and reduce heat transfer to the water-cooled combustor walls, the ramp and injection wall were coated with zirconia. Optical access to the test section was provided by three fused silica windows, two side windows normal to the injector wall, and one observation window opposite the injector wall. With the exception of the zirconia coating and the optical windows, all other surfaces were uncoated, water-cooled metal surfaces. The constant area test section downstream of the ramp base was $10H$ in length and was followed by a section of length $16H$ with a combustor wall divergence of 2.9 deg, giving a total test section length of $26H$. Two combustor extenders were available. One maintained a constant area from the end of the 2.9-deg divergent test section at $26H$ and had a length of $32H$. The second extender matched the 2.9-deg divergence at $26H$ with one wall diverging at 2.9 deg all the way to the tunnel exit at $58H$, with the same extender length of $32H$. The tunnel exited as a free jet into an open vertical pipe that exhausted through the roof of the building.

Figure 3 is a photograph of the dual-mode combustor taken during an experiment. The flow is from bottom to top, with the flame visible through the optical windows of the test section and above the extender as it exits into the exhaust pipe. Given figure reproduction quality, to is difficult to fully discern the flame features, but observations during the experiment confirmed that the flame was anchored at the base of the fuel injector. The flanged transition between the test section and the extender is seen in the middle of the photograph. Most of the tubing around the test section and extender contains high-pressure water for cooling the combustor during its continuous operation.

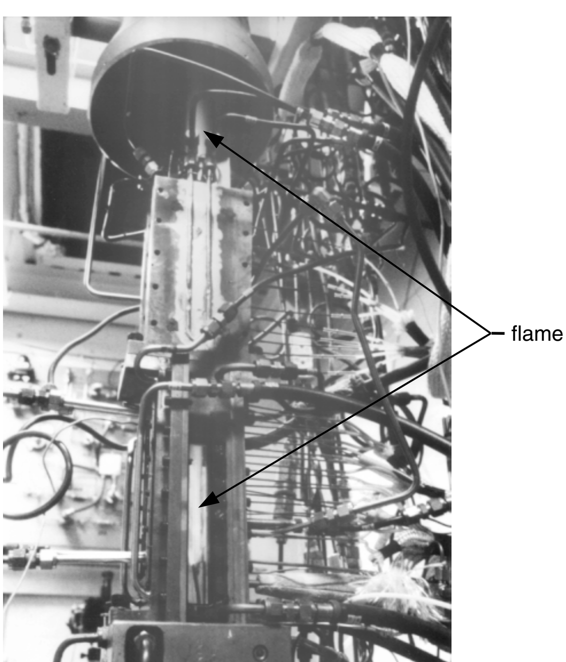

Fig. 3 Dual-mode scramjet combustor during supersonic combustion test.

For the combustion studies, the inlet air was heated to a total temperature of $T_0 = 1200$ K and the H_2 fuel was heated to $T_0 = 460$ K. Ignition under these conditions could be accomplished by one of two methods. Initial tests promoted ignition by adding H_2 fuel and reducing the air pressure from design conditions to move the shock train at the tunnel exit upstream into the test section, resulting in ignition in the region of the ramp leading edge. Following ignition, the air total pressure was then increased to design conditions, moving the shock train downstream. This procedure, however, tended to damage the optical windows. Ignition in the studies reported herein was accomplished by use of a combustion wave igniter supplied by the NASA John H. Glenn Research Center at Lewis Field. The igniter uses products of a premixed H_2–O_2 detonation that are injected normal to the tunnel axis downstream of the ramp. Following achievement of ignition and flame holding, a final adjustment of fuel temperature was made using a shell-and-tube heat exchanger downstream of the H_2 fuel heater. Combustor fuel equivalence ratio was determined to within $\pm 5\%$.

III. Experiments

A. Previous Measurements in Supersonic Combustion Facility

A number of measurements were obtained in this facility that have relevance to the studies on the influence of freestream contaminants undertaken in this investigation. Measurements have been obtained in rearward-facing step and unswept ramp geometries using classical measurements, including wall pressure and temperature measurements, and flame emission and advanced optical measurements. These include combustion efficiency determined from wall pressure measurement and the COMBAN code [13], time-resolved ignition measurements [14], spatially resolved OH concentration images using a KrF laser [15], spatially resolved OH imaging using a dye-based laser system [16], and measurements of OH velocity using a narrowband Nd:YAG pumped laser technique [17].

B. Nonvitiated Air Combustor Performance

A series of reacting flow tests were conducted to examine the characteristics of the combustor and to establish the desirable inlet conditions and combustor geometry to be used for the subsequent vitiation experiments. For the first tests the constant area $32H$ extender was installed downstream of the test section shown in Fig. 2. The coordinate X starts in the base of the ramp. A set of 29 pressure taps distributed along the injector wall was used to measure the pressure distribution along the tunnel axis. The first pressure tap is located at the nozzle exit, $X/H = -8$. The beginning of the ramp is at $X/H = -6$. The second tap is located on the ramp compression surface at $X/H = -5$ and the third in the base of the ramp, at $X/H = 0$. The remaining taps were located at X/H distances downstream of the base as shown in subsequent figures. The experimental uncertainty in the measured wall pressure was estimated to be $\pm 2\%$.

Figure 4 shows plots of static pressure on the combustor wall, normalized by the nozzle exit static pressure $P_{\rm ref}$, vs axial position. For these plots, the constant area extender was used. The plots are without injection and with injection and combustion for various inlet total pressures P_0 ($\pm 3\%$) at a fixed fuel/air equivalence ratio ϕ of 0.25. Air total pressure was varied over a range from 303 to 396 kPa. Without fuel injection, the ramp-induced shock wave reflects down the duct and the ramp base pressure is half the freestream static pressure. The flow is supersonic throughout most of the test section, and the normalized pressures upstream of the constant area extender ($X/H > 26$) are essentially identical for four air total pressures. In the constant area extender, shock trains are generated to match the

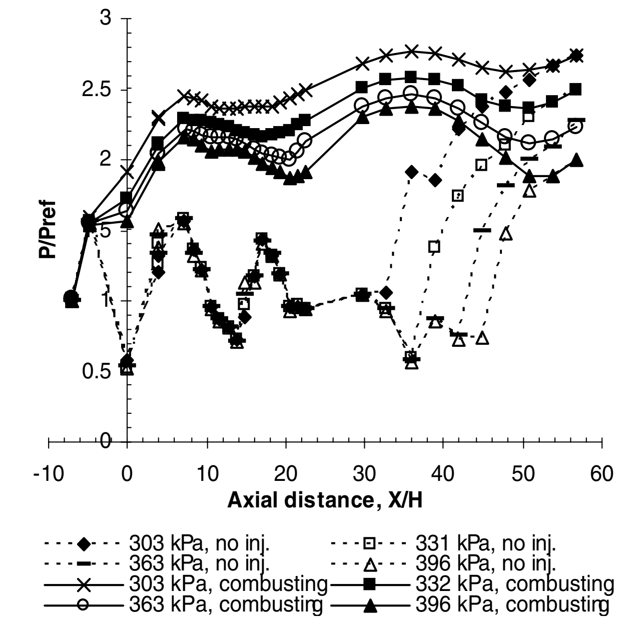

Fig. 4 Combustor axial pressure distribution, fixed $\phi = 0.25$, variable air P_0 listed in legend, constant area extender downstream of $X/H = 26$ (P_{ref} = static pressure at Mach 2 nozzle exit).

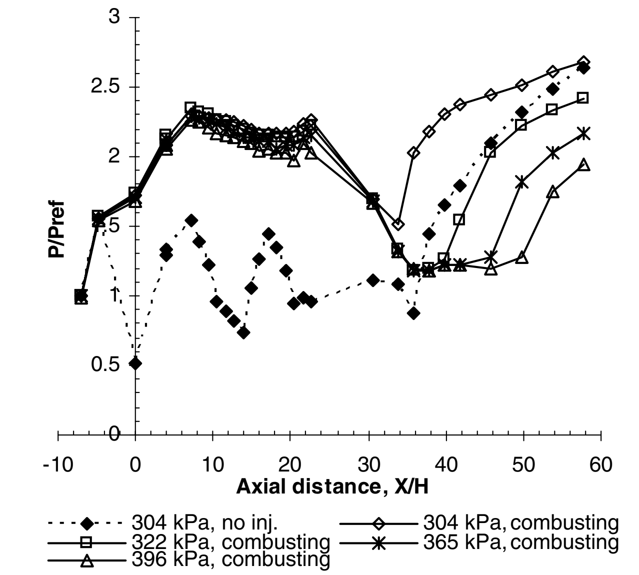

Fig. 5 Combustor axial pressure distribution, fixed $\phi = 0.25$, variable air P_0 listed in legend, 2.9-deg divergent extender downstream of $X/H = 26$.

atmospheric pressure at the tunnel exit. (Note that the reference pressure increases in proportion to the tunnel total pressure and therefore the normalized exit ambient pressures decreases, as is evident in Fig. 4.) The shock trains are forced downstream with increasing tunnel total pressure.

Ideally, the test section temperature and pressure distributions due to combustion and heat release would be similar for the various tunnel total pressures so that the test conditions would not be too sensitive to the pressure ratio (total to back) across the tunnel. The corresponding pressure distributions obtained with fuel injection and combustion are shown Fig. 4 for the same range of P_0 as the nonreacting cases at an equivalence ratio of 0.25. It can be seen that the flame is anchored at the base of the fuel injector because the pressure on the compression surface of the ramp ($X/H = -5$) is the same as in the nonreacting case. The base pressure ($X/H = 0$) has risen by a factor of 3–4 due to combustion. In the diverging section downstream of the constant area test section, the pressure rises, indicating a subsonic flow region against the combustion wall. The subsonic flow then adjusts to the ambient pressure in the constant area extender. This pressure distribution demonstrates that the heat release and associated pressure increase have resulted in a large subsonic zone on the combustor wall downstream of the fuel injector. The subsonic zone grows in the constant area extender due to the adverse pressure gradient. The bulk flow is not choked because the pressure rise is held in the base of the combustor. Thermal choking of the main flow would generate a shock train that would move upstream of the ramp, changing the pressure at $X/H = -5$. Most of the flow remains supersonic, except in this subsonic zone on the wall. The test section normalized pressure distributions are sensitive to the tunnel exit pressure (or tunnel pressure ratio) due the subsonic flow downstream of the test section that extends all the way to the extender exit. The test section conditions are coupled to the tunnel exit conditions through this subsonic region on the combustion wall.

To eliminate the effect of the tunnel pressure ratio on the test section conditions, the constant area extender was replaced with the 2.9-deg single wall divergence section, matching the divergence shown in Fig. 2. A similar series of experiments was conducted at various air inlet total pressures at fixed fuel equivalence ratio of 0.25. Figure 5 shows the results of the measurements obtained with the divergent extender. The addition of the extender has essentially eliminated the dependence of the test section conditions on the tunnel pressure ratio upstream of $X/H = 26$. The flow downstream of the subsonic zone on the wall behind the fuel injector now accelerates to supersonic conditions in the test section. The flow then compresses to the atmospheric back pressure through shock trains, which move downstream with increasing tunnel total pressure.

Previous numerical modeling of the flow [18] is depicted in Fig. 6 and helps to visualize the flow for the divergent extender configuration. Figure 6 shows very clearly why the test section conditions are isolated from the tunnel pressure ratio when the extender is divergent. When fuel is injected, but not ignited, as in Fig. 6a, the flow throughout the test section and extender is supersonic, except for the small recirculation region immediately downstream of the ramp fuel injector. When combustion takes place, as in Fig. 6b, a significant subsonic region downstream of the fuel injector forms against the injection wall. This region is confined

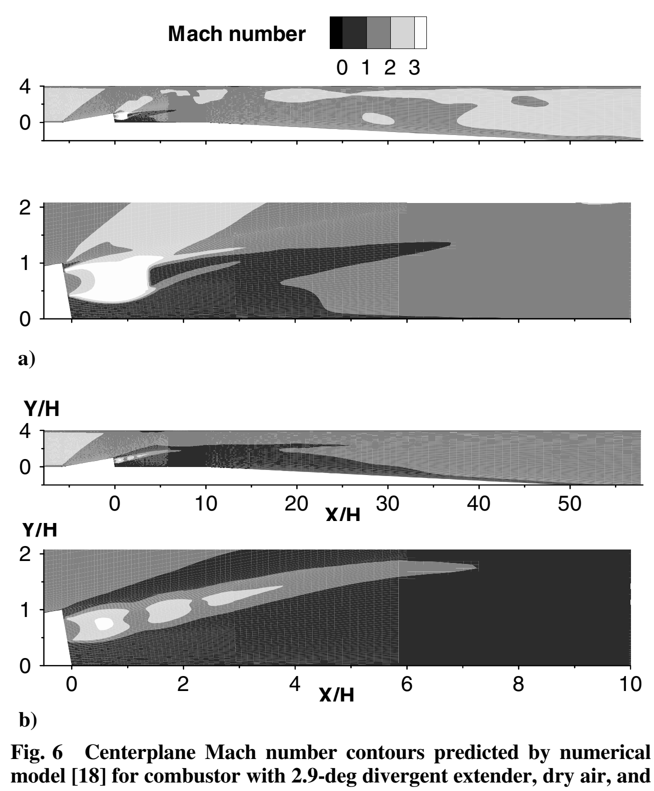

Fig. 6 Centerplane Mach number contours predicted by numerical model [18] for combustor with 2.9-deg divergent extender, dry air, and $\phi = 0.28$. Entire combustor and ramp region detail shown for a) fuel–air mixing and b) fuel–air combusting.

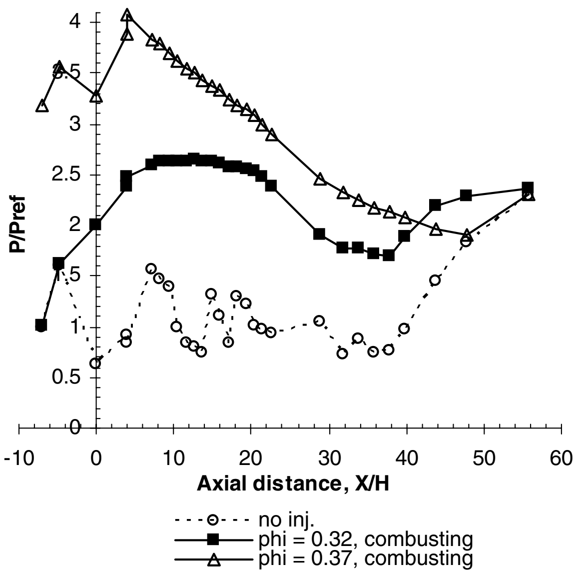

Fig. 7 Combustor axial pressure distribution; variable $\phi = 0$, 0.32, 0.37; fixed air $P_0 = 330$ kPa; combustor extender 2.9 deg divergent.

largely upstream of $X/H = 30$ due to a favorable pressure gradient in the divergent extender. Conditions at the tunnel exit can no longer propagate into the test section as they could with a large subsonic region all the way to the exit. Now the test section pressure distributions are essentially independent of the tunnel pressure ratio. Thus, based on the numerical and experimental results, the divergent extender was chosen for the remainder of the experiments reported herein.

Figure 7 shows wall pressure distributions for the combustor configured with the divergent extender for a fixed air total pressure, but variable fuel equivalence ratio. The fuel-off case shows a similar pressure distribution as in Fig. 5. The pressure distribution with equivalence ratio of 0.32 is very similar to that in Fig. 5 for $P_0 = 322$ and 365 kPa with a slightly lower equivalence ratio of 0.25. The higher equivalence ratio produces a higher injector normalized base pressure (2 vs 1.7), but is still representative of a local subsonic region against the combustor wall, followed by a reacceleration. The flowfield appears very similar to the one shown in Fig. 6b. The bulk flow remains supersonic and the pressure rise due to combustion is held around the base of the ramp. For the case of an equivalence ratio of 0.37, the combustor has transitioned to dual-mode operation. In the dual mode, the bulk flow is thermally choked by the heat addition and a precombustion shock train is generated. This shock train is positioned upstream all the way into the facility nozzle (the pressures at both $X/H = -8$ and -5 taps are now increased). With a length of only $2H$, the isolator is ineffective in holding the shock train. In an actual engine this could result in inlet unstart. The injector base pressure is now 3.3 times the nozzle exit static pressure. Downstream of the test section, the flow reaccelerates in the divergent section and matches the exit pressure through a weak shock. This demonstrates the mode transition that occurs at a fuel equivalence ratio between 0.32 and 0.37 in dry test gas.

C. Combustor Performance with Vitiated Air

Because H_2O is expected to influence the kinetics of the reaction significantly more than CO_2, and for a CH_4-fueled combustion heater H_2O is present at two times the molar concentration of CO_2, tests were primarily conducted using the addition of steam with a more limited series of tests including CO_2 vitiation. H_2O vitiate testing was initiated at low levels (1%) and ramped up over the testing program. Tests included direct comparisons of combustor performance, as determined by wall pressure and temperature distributions, lean flame holding limit, and flame emission observations. The addition of 1% steam to the airstream was noted to significantly decrease the intensity of the emission from the flame holding region in the base of the ramp and overall emission downstream. Addition of steam also shifted the lean flame holding limit (frequently extinguishing the flame), and altered the pressure distribution in the test section. The effect of CO_2 addition on the combustor performance was considerably less than that of H_2O. The addition of CO_2 reduced the wall pressures and affected the lean flame holding significantly less than H_2O; however, the CO_2 addition did produce a change in flame emission to blue from pale white.

Test section wall pressures were measured for various inlet air conditions at a fixed fueling rate sufficient to ensure flame holding with the addition of vitiates. Figure 8 shows typical plots of measured pressure, normalized by freestream static pressure, vs normalized axial position for three cases: dry inlet air, air vitiated with 5 mol percent H_2O, and air vitiated with 5% H_2O and 2.5% CO_2. Cases shown are without injection and with injection and reaction. Again, the pressure tap at $X/H = -8$ measures freestream static pressure, the tap at $X/H = -5$ measures the pressure on the compression ramp, and the tap at $X/H = 0$ measures the ramp base pressure. The fuel-off cases are shown in the figure, together with the fuel-on reacting cases. The fuel-off curves are the same as seen earlier (e.g., Fig. 7), with a small shift in the shock angles with 5% H_2O added. The three fuel-on pressure distributions with combustion are shown for three different inlet air compositions. With combustion, the pressure rises significantly in the base of the injector and downstream for all three cases. At a fuel equivalence ratio of 0.27, the three pressure distributions are similar to those in Fig. 5 with a fuel equivalence ratio of 0.25. The bulk flow is supersonic and adjusts to the ambient back pressure through shock trains. Downstream of the injector all three plots are similar, with the influence of the vitiates evident as a reduction of pressure. At the end of the constant area of the test section ($X/H = 10$), the pressure decrease relative to the dry air case is 10% with 5% H_2O and 12% with 5% H_2O and 2.5% CO_2. For these conditions, therefore, H_2O is about 2.5 times more effective at reducing the combustion-generated pressure than CO_2. This is consistent with the chemical kinetics in that H_2O is four times more efficient than CO_2 in the chain terminating reaction that forms HO_2. The overall pressure reduction due to the vitiates in Fig. 8 can be attributed to both finite-rate chemical kinetics and to thermodynamics (increase in mixture specific heat and increased dissociation of the contaminant species [19]). More detailed measurements are needed to understand the relative contribution of these two effects. Pressure distributions obtained at lower vitiate levels than those in Fig. 8 demonstrated a proportional reduction in pressure due to vitiates.

Figure 9 shows the wall pressure distributions for dry air and for air vitiated with 7% H_2O at a fuel equivalence ratio of 0.35. At this high

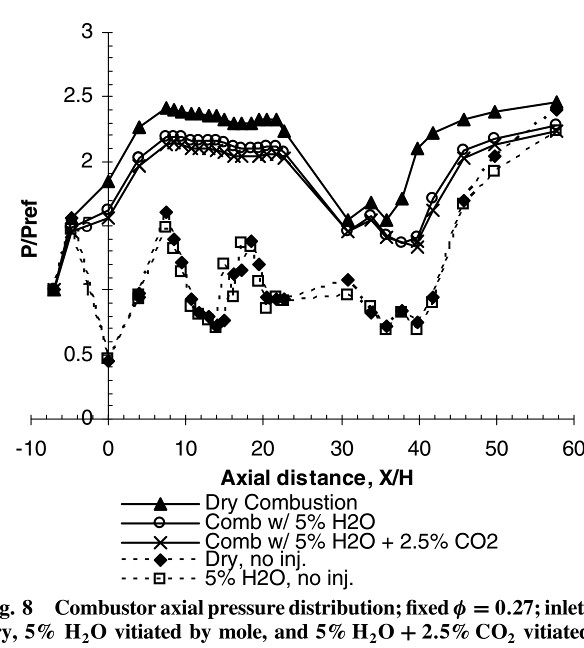

Fig. 8 Combustor axial pressure distribution; fixed $\phi = 0.27$; inlet air: dry, 5% H_2O vitiated by mole, and 5% $H_2O + 2.5\%$ CO_2 vitiated by mole; combustor extender 2.9 deg divergent.

fueling rate, the dry air curve indicates a thermally choked flow, with the shock train attached to the leading edge of the fuel injector. Note that the shock train is held on the fuel injector for this equivalence ratio, whereas it propagated into the facility nozzle at the slightly higher equivalence ratio of 0.37 (as depicted in Fig. 7). The subsonic flow downstream of the thermal choke accelerates in the diverging channel and matches the ambient pressure at the exit via a weak shock. The dry air case represents dual-mode operation. With vitiated air the pressure distribution is very similar to that with dry air at a slightly lower equivalence ratio of 0.32 (see middle plot in Fig. 7). The flow is supersonic, with a subsonic region on the combustion wall (see Fig. 6b numerical result for dry air at a lower equivalence ratio). The vitiated air case is representative of the supersonic mode of operation. By adding only 7% H_2O, the dual mode has transitioned to the supersonic mode. Such mode transition has been previously demonstrated by variation of air inlet temperature using combustion preheated air [20]. The current demonstration is the first in which chemical composition of the inlet air has controlled this transition.

An approximate Rayleigh analysis was conducted for the results of Fig. 9. State 1 is taken at the combustor inlet where the Mach number is 2 ($X/H = -8$). State 2 is taken at the end of the constant area test section ($X/H = 10$). For dry air, state 2 is choked because the normalized pressure required to choke is 2.7 and the pressure ratio at state 2 is 3.2 in Fig. 9. The energy required to drive the dry air to the choked state is calculated, and that amount of energy is assumed to be added to the vitiated air. This gives the Mach number at state 2 of 1.08 and a normalized pressure of 2.5 for the vitiated air. The measured pressure ratio at state 2 for the vitiated air is 2.2 in Fig. 9. Experimentally, the pressure decrease from dry air to vitiated with 7% H_2O is 31% and the Rayleigh calculation gives 22%. This approximate calculation would suggest that, in a 1-D sense, most (on the order of 70%) of the pressure decrease due to vitiation is attributable to thermodynamics and the rest (on the order of 30%) to chemical kinetics.

The importance of this mode transition due to vitiation is as follows: At the fueling rate and conditions of Fig. 9, data obtained in ground test facilities using the vitiated air would indicate that the combustor would operate in the supersonic mode, whereas in flight under the same conditions, the combustor would be dual mode. Note that this was observed for only 7% H_2O, whereas a vitiated facility producing Mach 5 enthalpy would contain closer to 13% H_2O. The experimental facilities using vitiated air will observe transition to the dual mode at a higher fuel equivalence ratio than in flight. Extrapolating a vitiated air result to flight could result in overfueling of the combustor. If the engine isolator cannot hold the resulting precombustion shock train, the shock train could move into the inlet, causing inlet unstart.

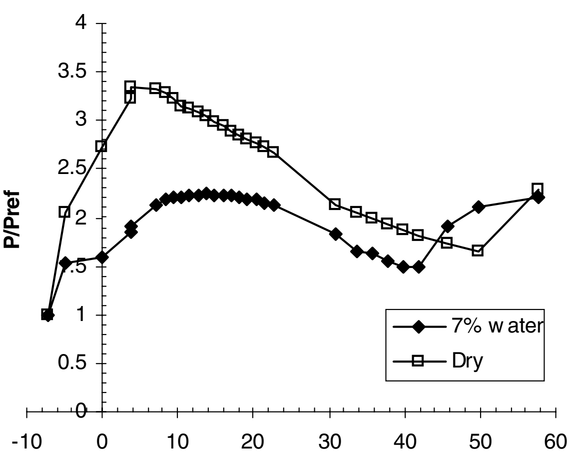

Fig. 9 Combustor axial pressure distribution, fixed $\phi = 0.35$, inlet air: dry combustion and 7% H_2O vitiated by mole, fixed ϕ and air P_0, combustor extender 2.9 deg divergent.

IV. Conclusions

The influence of major species contaminants introduced by combustion air preheaters on supersonic reacting flows was evaluated by conducting a controlled set of experiments in a model combustor. The facility in which the experiments were conducted provides a unique clean and dry source of air heated electrically to 1200 K. The facility was modified to permit controlled amounts of common major species, H_2O in the form of steam and gaseous CO_2, to be mixed with makeup O_2 and heated with the air. Combustion experiments were conducted in a test section using an unswept 10-deg ramp with Mach 1.7 hydrogen fuel injected from the base into a Mach 2 combustor inlet flow. Inlet gas composition was varied from dry air to vitiated air with 5% H_2O and 2.5% CO_2 and vitiated air with 7 % H_2O.

Significant findings from these studies are as follows:

1) Pressure distributions in the combustor test section were sensitive to the tunnel pressure ratio (total to ambient) with a constant area extender. This was due to a subsonic zone on the combustor wall that extended all the way to the tunnel exit. Using a 2.9-deg divergent extender accelerated the combustion gases, greatly reducing the downstream extent of the subsonic zone and eliminating the test section sensitivity to the tunnel pressure ratio.

2) With dry air, the combustor operated in the supersonic mode for a fuel equivalence ratio of 0.25–0.32. The flame was held at the base of the fuel injector in a subsonic combusting zone. The main flow remained supersonic, accelerating in the divergent extender.

3) With dry air, the combustor operated in the dual mode for a fuel equivalence ratio of 0.35–0.37. A precombustion shock train propagated into the facility nozzle for the higher equivalence ratio. The short isolator, two ramp injector heights in length, was ineffective at holding the shock train. The main flow was largely subsonic, but accelerated to supersonic conditions in the divergent extender.

4) At a fixed fuel equivalence ratio of 0.27, the combustor operated in the supersonic mode for the dry and two vitiated cases: 5% H_2O and 5% H_2O plus 2.5% CO_2. The combustor pressure distribution decreased in magnitude by 10% with 5% H_2O vitiation and another 2% when 2.5% CO_2 was added. It was concluded that, for the conditions studied, H_2O is approximately 2.5 times more effective at reducing the combustion-generated pressure than CO_2.

5) For a fuel equivalence ratio of 0.35, the combustor operated in a dual mode with dry air, but in the supersonic mode when vitiated with 7% H_2O. An approximate Rayleigh calculation for this case predicts that on the order of 70% of the measured pressure decrease with vitiation was due to thermodynamics and 30% to chemical kinetics. This is the first demonstration of mode transition due to flow contaminants.

6) For the conditions studied, it is concluded that ground facility tests with vitiated air observe transition from supersonic to dual mode at a higher fuel equivalence ratio than in flight. Extrapolating vitiated air measurements to flight could result in overfueling of the combustor and possible inlet unstart.

Understanding the complex issues related to the influence of airstream vitiates on test results will require a coordinated effort, including experiment and modeling. Using the data presented herein, numerical models that include both the effects of finite-rate kinetics and thermodynamics on the combustor operating conditions can be validated and calibrated. With confidence in the numerical method, the two effects can be separated out by first assuming equilibrium chemistry and then slowly adjusting the kinetics. This would be extremely useful at improving understanding of the complex effect of vitiates in ground test facilities.

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