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Technical Notes

Experimental Study of Vitiation Effects on Scramjet Mode Transition

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I. Introduction

MANY ground test facilities for studying dual-mode scramjet (DMSJ) propulsion rely on stagnation enthalpy simulation via combustion of hydrogen or hydrocarbon fuel. This heating process results in levels of vitiates in the test flow, such as water and carbon dioxide, that are not present in atmospheric air. The effects of these vitiates on DMSJ performance and operability must therefore be understood if accurate extrapolations to flight can be made. The Supersonic Combustion Facility [1] provides a unique opportunity to study such effects since the facility is electrically heated and supplies a test gas that is free of combustion generated vitiates. However, water vapor, in the form of steam, and carbon dioxide can be added to the flow to examine the effects these vitiates have on a DMSJ. Previous work to study vitiation effects has been performed using up to 7% H_2O and 2.5% CO_2, both by mole [1]. However, these results were only obtained over a limited range of fuel equivalence ratios and the study did not fully investigate mode-transition with a precombustion shock train due to the lack of a flowpath isolator. The present study was conducted with vitiate levels closer to those encountered in combustion heated facilities and with an isolator installed. Reference [2] provides details of the new configuration. Basically it consists of the DMSJ of [1], a rectangular, direct connect combustor with a single ramp fuel injector, and a new constant area, rectangular isolator that is ten duct heights long. This Note reports on experimental pressure measurements in the scramjet combustor at two vitiated conditions and compares the results with that of clean air. Water and carbon dioxide levels are examined such that the effects of water vapor vitiation can be isolated for conditions that are representative of a methane combustion heated facility operating at Mach 5 simulation. Trends in the data are examined, particularly with respect to the effect vitiates have on the mode-transition characteristics of the DMSJ.

II. Results

Axial pressure distributions are presented in order to examine the effects of vitiates on mode-transition. Details on the direct connect configuration, instrumentation and data acquisition system can be found in [3]. A schematic of the DMSJ is provided in Fig. 1. At the exit of the Mach 2 nozzle, the duct height and width are 1 and 1.5 in., respectively, and the isolator is 10 in. long, with an additional 0.5 in. prior to the leading edge of the ramp fuel injector.

Pressure distributions for the DMSJ are presented in Fig. 2 for a hydrogen fuel equivalence ratio of $\Phi = 0.26$. This Φ was selected because it is the equivalence ratio that, for clean air, results in the classic dual-mode, or ramjet, mode of operation, i.e., a precombustion shock train in the isolator that terminates with a normal shock. Three pressure distributions were measured while combusting for: 1) clean air, 2) air vitiated with 9% H_2O, and 3) air vitiated with both 9% H_2O and 4% CO_2, where all percentages are by mole. The latter vitiation condition is equivalent to a methane combustion heated facility operating at Mach 5 enthalpy simulation. To account for the differences in test gas composition, fuel mass flow rate was adjusted to maintain a constant Φ for the three cases. The fueloff pressure distribution is shown for reference in Fig. 2. $X/H = 0$ is at the base of the ramp fuel injector where $H = 6.4$ mm and is the normal height of the ramp fuel injector (the duct height is $4H$). All pressures are normalized by P_{ref}, the measured isolator inlet pressure to provide a consistent basis for comparison across different test conditions. As further explained in [3], wall pressures were monitored using a Pressure Systems, Inc., NetScanner system. Considering systematic and precision errors, total experimental uncertainty of measured pressure was estimated to be $\pm 2\%$, and the uncertainty of the normalized pressures of Fig. 2 is close to $\pm 3\%$, or about the same size as the symbols found on Fig. 2.

To aid interpretation of the experimental results, a one-dimensional analysis of the DMSJ was performed using the approach of [4]. Using this method, mode-transition could be identified from the measured wall pressures. Following [4], five stations were identified in the DMSJ; station 2 at the isolator entrance, station 3 at the entrance to the combustor (and the point of fuel injection) and station 4 at the exit of the burner (see Fig. 1). Additionally, during mode-transition, there is a precombustion shock train with a leading edge at station u, between stations 2 and 3, and a trailing edge at station d, at or downstream of station 3. When a thermal throat is formed due to the heat release of combustion, between stations 3 and 4, mode-transition takes place. In this ramjet mode, stations 3 and d become coincident, the precombustion shock train terminates with a normal shock and the combustion process becomes subsonic. Conversely, in the scramjet mode, the flow in the combustor remains supersonic in a one-dimensional sense and there are two possible cases: 1) no shock train or 2) a shock train that terminates with an oblique shock. For the former case, stations u and d are downstream of 3, for the latter, u is upstream of 3 and typically d is downstream of 3. From [4], the Mach number at station d can be calculated using a control volume analysis of the isolator. In the analysis here, we additionally take into account the effect of the isolator boundary layer by performing a Fanno calculation upstream of the isolator shock train. For a fixed Mach number at station 2, the Mach number at the entrance of the combustor (station 3) is a function only of the ratio of specific heats of the test gas and the pressure ratio across the isolator. This Mach number was calculated for the combustion cases of clean air, air vitiated with 9% H_2O, and air vitiated with both 9% H_2O and 4% CO_2, in addition to clean air with fueloff. These results are presented in Fig. 3. The ratios of specific heats used for the calculations were 1.34 for clean air, 1.33 for air vitiated with 9% H_2O and 1.31 for air vitiated with both 9% H_2O and 4% CO_2. It can be seen in the figure that the combustor entrance Mach number is subsonic for the clean air combusting case but is supersonic for the other three cases. Therefore, it is concluded that the presence of vitiates, at the levels listed, resulted in the combustor transitioning

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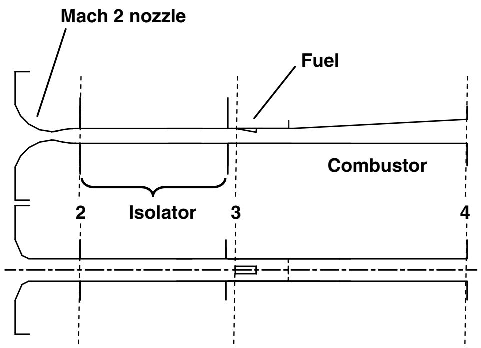

Fig. 1 Schematic of the direct connect DMSJ with stations 2, 3 and 4 identified for one-dimensional analysis.

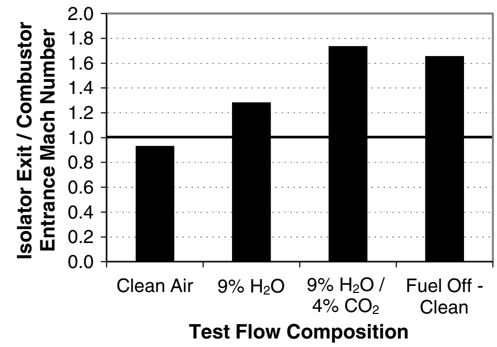

Fig. 3 Calculated combustor entrance (station 3) Mach number using measured pressures and one-dimensional theory for various test flow compositions.

modes from the ram mode to the scram mode of operation. By examining the measured pressure distributions in light of this information, additional conclusions can be drawn.

Returning to Fig. 2, the fueloff pressure distribution for clean air is consistent with supersonic flow throughout the entire DMSJ assembly and the calculation described. There is an oblique shock attached to the fuel injector, represented by a pressure rise at $X/H = -5$. Downstream of the fuel injector are a series of reflected shocks and expansion fans that are generated by the ramp fuel injector. At $X/H = 30$ there is a shock train that adjusts the flowpath pressure to the 1 atm back pressure at the exhaust of the combustor.

For the combusting case with clean air, the precombustion shock train begins at $X/H = -20$, reaches a P/P_{ref} of 3.6 at the point of fuel injection, then decreases until the second shock train that matches the atmospheric back pressure. The drop in pressure at $X/H = 0$ is due to the pressure tap being located in the recirculation region at the base of the fuel injector. According to the one-dimensional analysis presented, the combustor is operating in the ram mode with a precombustion shock train that terminates as a normal shock. The pressure distribution measured for this case is consistent with the ram mode of operation (as described in [4]).

With 9% H_2O in the air flow, the precombustion shock train has moved downstream relative to clean air and begins at $X/H = -10$. The maximum P/P_{ref} in the combustor decreases by 17% to 3. Behavior similar to clean air is exhibited at the aft end of the combustor, with a pressure decrease and a shock train to the atmospheric back pressure. The pressure rise due to combustion is still upstream of the leading edge of the ramp fuel injector. According to the one-dimensional analysis, the combustor entrance Mach number at station 3 is 1.3 and hence the DMSJ is operating in the scramjet mode. In addition, since there is a pressure rise upstream of the fuel injector, but the combustor is supersonic, the precombustion shock train is oblique and does not terminate with a normal shock. Again, the measured pressure distribution for this mode of operation is consistent with [4].

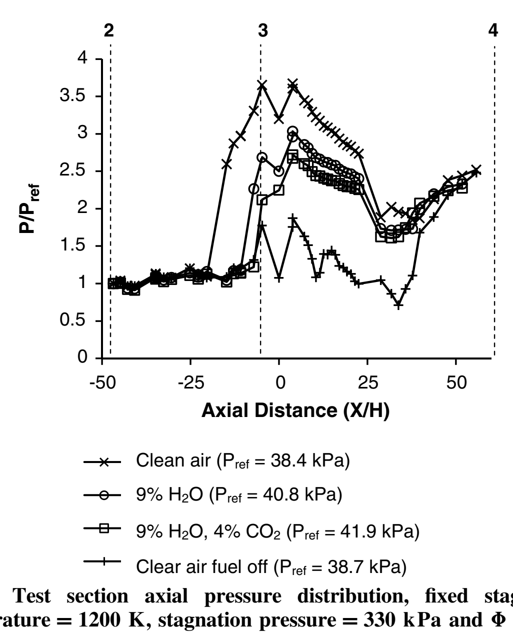

Fig. 2 Test section axial pressure distribution, fixed stagnation temperature = 1200 K, stagnation pressure = 330 kPa and $\Phi = 0.26$. Stations 2, 3 and 4 identified for one-dimensional analysis.

With 9% H_2O and 4% CO_2, the combustor has transitioned to the scramjet mode with no precombustion shock train. There is no combustion induced pressure rise upstream of the ramp fuel injector leading edge. With the addition of CO_2, the peak combustor P/P_{ref} is reduced by a further 10%. However, the overall change in the axial pressure profile is smaller than for the addition of H_2O alone.

As the level of vitiates in the flow is increased, the pressure rise due to the presence of combustion decreases in magnitude. The shock train also becomes shorter as the flow is increasingly vitiated. With combustion, the DMSJ operated in the ram mode for the clean air case, the scram mode with an oblique precombustion shock train for the 9% H_2O case and in the scram mode with no precombustion shock train for the 9% H_2O and 4% CO_2 case. Both water vapor and carbon dioxide have higher specific heat capacities than air. The specific heat for clean air and that vitiated with 9% H_2O and 9% H_2O with 4% CO_2 is estimated to be 1142, 1208, and 1215 $\mathrm{J\,kg^{-1}\,K^{-1}}$, respectively. For a similar energy input delivered through combustion, a higher specific heat reduces the temperature of the bulk flow. The reduced temperature of the flow is reflected in the decrease in combustor pressure, and an increase of combustor Mach number, as the percentage of vitiates in the flow increases. Chemical kinetic effects are additionally possible. As discussed in [1], both water vapor and carbon dioxide can increase ignition delay with the effects being smaller for carbon dioxide. Therefore, both thermodynamic and chemical kinetic effects trend in the same direction. However, the relative thermodynamic and chemical kinetic effects are not addressed in this study since the ability to experimentally measure the presence and levels of radical species is unavailable.

The results presented in this Note are consistent with the trends in [1]. For the DMSJ without an isolator, the addition of 7% H_2O by mole changed the combustor operation by lowering the peak combustor pressure and modifying the pressure profile. The addition of the isolator in this study changes the magnitudes of the pressures due to changing the combustor upstream conditions, but the general trends of pressure decreasing with added vitiates remains consistent. However, since the present experimental configuration includes an isolator, the present results show that vitiates have an effect on the mode of operation, the isolator shock train length, and the combustor peak pressure levels. Additionally the presence of carbon dioxide shortens the shock train and lowers combustor pressures over that of water vapor alone.

III. Conclusions

This Note presents the first experimental results demonstrating the effects of both water and carbon dioxide vitiation on DMSJ mode-transition. For $\Phi = 0.26$, the combustor operates in the classic ram mode with a shock train in the isolator that terminates with a normal shock. Adding vitiates in the form of 9% H_2O by mole reduces the combustor peak pressures and shock train length and transitions the DMSJ to scram mode. Combustion transitioned to the scram mode with no precombustion shock train with the addition of 4% CO_2 on top of the 9% H_2O.

The presented results demonstrate significant differences in the combustion properties of the DMSJ with vitiated and clean air, emphasizing the importance of understanding vitiate effects. The presence of carbon dioxide in hydrocarbon vitiated facilities will have an effect on mode-transition, demonstrating that both water vapor and carbon dioxide need to be accounted for. Therefore, dual-mode scramjet combustor studies performed using vitiated facilities must take into account vitiation effects before the results are extrapolated to flight. Because vitiates were found here to affect mode of operation, shock train length and pressure rise. The effects on DMSJ control, operability, isolator margin, fuel schedule and thrust must all be considered for operation in flight in clean atmospheric air. Observed trends in this study are consistent with thermodynamic effects but further study, particularly analytical or numerical analyses where chemical reaction rates can be modified, is required in order to examine differences in the flow and determine relative chemical kinetic effects. Such studies may also enable an examination of the effects of vitiation on the mixed subsonic and supersonic nature of the flow that is typical of a DMSJ but is not captured in the one-dimensional analysis of this study.

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