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Physical Simulation Of Rocket Exhaust Aerodynamics Using Heated Ethane:

Prototypical Experiments

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SUMMARY

An inaugural experimental investigation into the use of heated ethane as a motive fluid for subscale simulation of rocket exhaust plume aerodynamics has been conducted. A small, self-contained, hydrocarbon aerodynamics test stand was designed and fabricated for this purpose. Testing was performed on an aerodynamic system comprised of a 77:1 upper stage nozzle contour coupled with a passive second-throat supersonic diffuser, specifically selected for its known LO_X/GH_2 hot-fire performance and complex shock structure. Effects of ethane purity and stagnation temperature on the accuracy of flow field replication have been examined. All major flow features present in hot-fire tests were reproduced in heated ethane with start and unstart pressure ratio errors of approximately +4% and -5%, respectively. Steady-state test cell pressure ratio errors of ±0.5% were shown to be readily achievable when the stagnation temperature was well-controlled. Ambient-temperature nitrogen testing was also conducted for the purpose of direct comparison of the ethane method to conventional cold-flow techniques. However, its higher isentropic exponent prevented the diffuser from achieving start.

NOMENCLATURE

FSS	Free Shock Separation
HPDS	Hydrocarbon Propellant Delivery System
GH_2	Gaseous Hydrogen
LO_X	Liquid Oxygen
P	Pressure
RSS	Restricted Shock Separation
T	Temperature
TOP	Thrust Optimized Parabolic

Subscripts

AMB	Ambient Condition
CELL	Test Cell Condition
ETH	Ethane
HF	Hot Fire
WALL	Wall Condition
0	Stagnation Condition

BACKGROUND

Simulated-altitude testing of rocket engines at NASA's Stennis Space Center (SSC) often requires the design of supersonic diffusers. Validation of diffuser aerodynamic performance via subscale experimentation has historically been considered a necessary risk-mitigation procedure prior to their use in testing flight hardware. Because nitrogen, air, and steam are poor analogs for rocket exhaust, SSC's subscale diffuser test programs have typically been performed with chemically reactive propellants and water-cooled nozzles, at great cost [1-4].

In an effort to reduce the temporal and monetary resources required for accurate assessments of diffuser performance, the author proposed the use of heated hydrocarbons as motive fluids in lab-scale experimentation. Ethane in particular was found to be a suitable simulant of rocket effluent as its isentropic exponent throughout a supersonic expansion process could be manipulated to closely approximate that of combustion products. The details of the concept were discussed in a NASA Technical Memorandum released in 2019 [5]. To confirm its validity, SSC commissioned the design and fabrication of a portable hydrocarbon test bed at Purdue University. The Hydrocarbon Propellant Delivery System (HPDS) was activated in late 2019 and used to perform ethane aerodynamics experiments on the Purdue campus throughout 2020. This paper presents results of the first aerodynamic configuration examined during that time.

EXPERIMENTAL APPARATUS

The HPDS was designed to be a compact, largely self-contained unit capable of testing ~2.5% scale rocket nozzles and any plume management systems of aerodynamic relevance. For this test series, nitrogen was supplied to the stand via facility connection for purges and pressurization, and ethane was sourced from a K-type cylinder. Liquid ethane was transferred from the bottom of the bottle via dip tube to a 28 L, piston-style run tank where it was pressurized prior to heating. Two insulated pebble beds filled with 6.4 mm stainless steel spheres and each wrapped with ~1 kW electrical resistance heaters were used to vaporize and stabilize the ethane at a specified temperature. A short length of insulated tubing was installed between the second pebble bed heater and a small thrust takeout structure. Control of the various valves and regulators were managed by an onboard computer and accessed via LabVIEW interface. LabVIEW also governed low-speed (1.0 kHz) temperature and pressure data acquisition. The entire system was mounted on a hurricane-resistant steel frame which was designed for the case of transportation and placement via forklift.

Fig. 1 – CAD model of the HPDS (left), and a photograph of the system taken during testing (right).

TEST ARTICLE

The aerodynamic configuration selected for this test series consisted of a truncated thrust-optimized parabolic (TOP) nozzle [6,7] coupled with a passive second-throat diffuser which exhausted directly to the atmosphere. The full nozzle profile extended to an expansion ratio of ~275:1 but was truncated at an area ratio of 77:1, resulting in a high exit half-angle of ~19°. The geometric scale of the ethane test article was set at 13.7% relative to hot-fire subscale testing previously performed at SSC's E-3 test facility and 2.5% relative to flight hardware. All components were fabricated from stainless steel. Test article hardware is shown in Fig. 2, and corresponding internal dimensions are given in Fig. 3. The nozzle throat had a diameter of 3.175 mm and passed ~0.075 kg/s of ethane during steady operation.

The diffuser was affixed at the nozzle exit plane with the interior profile offset radially from the nozzle lip. A void was milled upstream of the diffuser inlet to reproduce the proportional volume of a simulated clamshell used during hot-fire testing. The diffuser-inlet-to-nozzle-throat area ratio was 107, the second throat contraction ratio was 0.46, and the expansion ratio of the subsonic diffuser was 1.82. The ratio of diffuser length to second throat diameter was 14. Instrumentation bosses were distributed along the diffuser with the intent to approximate the placements during hot-fire testing, though some compromises were necessary due to the tight spacing at the small scale.

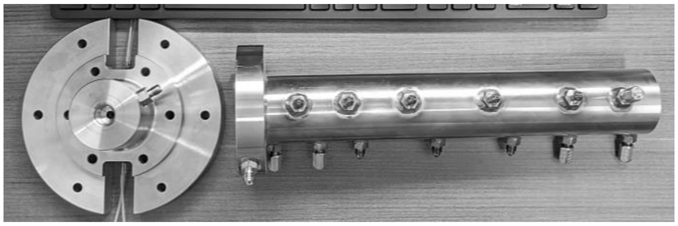

Fig. 2 – Ethane-scale test article hardware with a keyboard at the top of the photo for scale.

Fig. 3 – Ethane-scale test article aerodynamic geometry with lengths given in mm.

RESULTS AND DISCUSSION

SSC's previous hot-fire testing of the rocket-diffuser system was performed with a LO_X:GH_2 mass ratio of 6.05. Attempts to replicate the observed aerodynamics with ethane were undertaken, and the effects of stagnation temperature on pressure error were evaluated. Sensitivity to contamination was assessed using two commercially available grades of ethane: pure and technical. The pure ethane was guaranteed by the supplier to have a contamination level of less than 0.01% by mass, while the technical grade was labeled as containing a minimum of 98.5% ethane. Its composition was later established as 99.51% ethane, 0.47% propane, and 0.02% methane with negligible amounts of other species present.

Test-cell-to-stagnation pressure ratio is the most important variable for the evaluation of diffuser performance. Plots of this quantity as a function of the stagnation-to-ambient pressure ratio are commonly known as 'pumpdown curves' which can show the transient development of the shock structure within the driving nozzle as well as diffuser start, steady-state pumping, and hysteresis effects. Interpretation of pumpdown data is simplified by the fact that it is definitionally recorded upstream of all shock reflections within the diffuser. This precludes any uncertainty associated with sensor position relative to shock structure. For these reasons, the test cell pressure ratio was selected as the primary variable of interest for quantitative evaluation of ethane's performance as a simulant.

Diffuser pumpdown curves for hot-fire and ethane are compared in Fig. 4, with notable flow phenomena annotated. Slight deviations were observed beginning in the restricted shock separation (RSS) portion of the pumpdown and continuing through diffuser start, though there was overall agreement in the trends. Some portion of this difference is likely attributable to the slow ethane chamber pressure rise relative to the system's mean residence time. Accounting for the differences in gas properties and the scale of the hardware, the ethane diffuser was brought to the start condition ~30 times slower than hot fire. This essentially guaranteed that the ethane system reached an aerodynamic steady state at each incremental chamber pressure - a condition not achieved during the hot-fire tests. The pressure ratios required to start and unstart the diffuser were reproduced with errors of +4% and -5%, respectively, and were not sensitive to stagnation temperature or ethane purity over the range tested. These invariances are shown in Fig. 5.

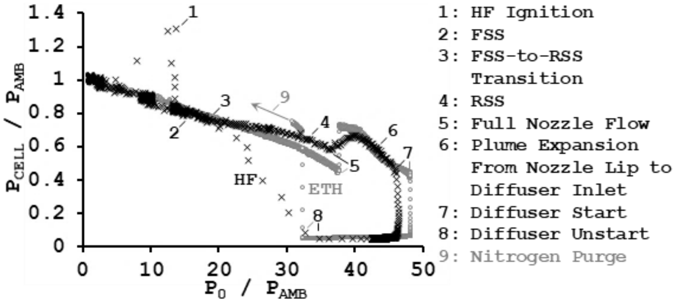

Fig. 4 – Comparison of diffuser pumpdown curves produced by ethane and combustion products.

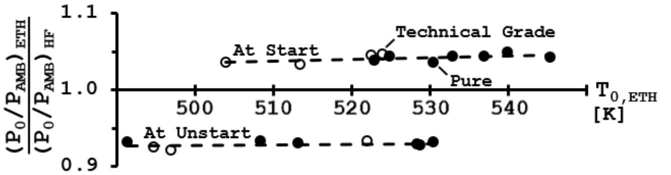

Fig. 5 – Effect of ethane stagnation temperature on diffuser start and unstart, compared to hot-fire tests.

Ethane was also found to be an adequate hot-fire analog with respect to steady-state diffuser performance. Fig. 6 shows the variation of test cell pressure ratio error with stagnation temperature. Error was driven to ±0.5% during multiple tests over the stagnation temperature range of 530 K to 537 K, with a mean of null-error temperature of 534 K. Contaminants in the technical grade ethane had minimal aerodynamic effect. This was consistent with quasi-1D equilibrium flow analysis performed with the NASA Chemical Equilibrium with Applications code [8], which predicted a test cell pressure difference of ~0.2% between the two grades of ethane. Confirmation of this insensitivity established the use of technical-grade ethane as the default for production testing and reduced the per-test propellant cost by a factor of three.

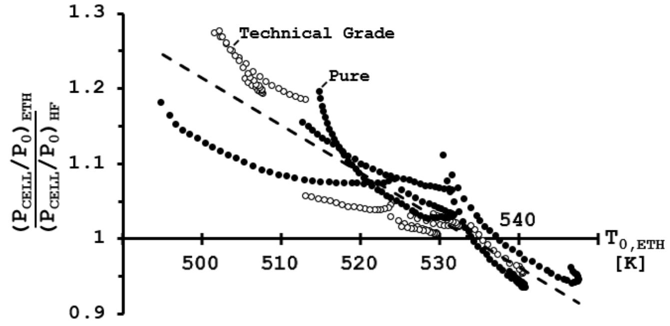

Fig. 6 – Effect of ethane stagnation temperature on steady-state test cell pressure ratio, compared to hot-fire tests.

Downstream of the test cell, ethane-produced wall pressures indicated the same shock structure observed in the hot-fire system. Ethane was able to reproduce the location and magnitude of plume impingement, the subsequent supersonic reacceleration through the diffuser's contraction, the oblique shock reflections within the second throat, the location of boundary layer separation, and the subsonic pressure recovery through the divergent section. This is shown in the left plot of Fig. 7. Steady-state CFD simulations were performed using the Loci/CHEM code [9,10] to serve as a data interpretation aid. Visualizations of log(P) are displayed alongside the wall pressure plots. Overall, deviations from hot-fire data were minimal, though the higher ethane pressure at the beginning of the second throat may suggest a stronger centerline Mach reflection caused by localized condensation.

Several tests were also conducted with ambient nitrogen to enable a 1:1 comparison of ethane to conventional cold-flow methodology. However, the second throat was sized to pass hot rocket exhaust and its cross-sectional area was too restrictive to 'swallow' the starting shocks. The right plot of Fig. 7 shows a comparison of the wall pressures generated by nitrogen and hot fire. The original intent of nitrogen testing was to quantitatively demonstrate that the simulant-induced pressure error was much lower for ethane in a supersonic system. However, it is possible that the result of a non-started diffuser provided a clearer qualitative illustration of that fact, as nitrogen's high isentropic exponent renders the system effectively untestable via conventional cold-flow techniques.

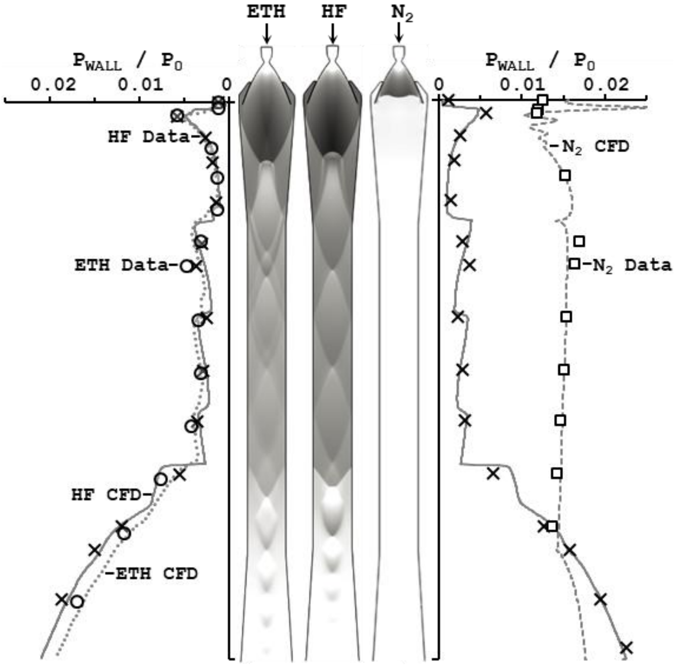

Fig. 7 – Comparison of hot-fire ($LO_X:GH_2=6.05$), ethane (13.7% scale, $T_0=539$ K), and nitrogen (13.7% scale, $T_0=301$ K) wall pressure ratios at $P_0/P_{AMB}=48.4$.

CONCLUSIONS

The described experiments have demonstrated the utility of heated ethane in the physical simulation of rocket plume aerodynamics. Flow features observed in a LO_X/GH_2 rocket-diffuser system were successfully replicated in ethane, including transient pumpdown performance, internal shock structure, and boundary layer separation. Test cell pressure ratio errors of ±0.5% were repeatedly achieved by the tuning of ethane's isentropic exponent via adjustment of its stagnation temperature.

Nitrogen testing of the system resulted in a diffuser non-start condition which provided a clear illustration of ethane's advantage over conventional cold-flow methodologies. It is expected that this new method will be extensible to a variety of other propellant combinations, and that heated hydrocarbon testing will prove a useful addition to the subscale aerodynamics toolkit.

FUTURE WORK

Ethane testing of several additional aerodynamic configurations is currently underway. Further results will be published upon completion. Upon conclusion of validation experiments, the HPDS will likely serve as an ethane supply for wind-tunnel investigations of human-rated Mars lander supersonic retropropulsion.

REFERENCES

[1] Jones, D., Allgood, D., and Saunders, G.P., "Passive Rocket Diffuser Testing: Reacting Flow Performance of Four Second-Throat Geometries", NASA TM 2016-219221, DEC 2016.

[2] Saunders, G.P., "A3 Subscale Diffuser Test Article Design", AIAA-2009-5010, 2009.

[3] Saunders, G.P. and Wagner, D.A., "A3 Subscale Steam Ejector Performance Testing", AIAA-2009-5100, 2009

[4] Saunders, G.P. and Yen, J., "A3 Subscale Rocket Hot Fire Testing", AIAA-2009-5099, 2009.

[5] Jones, D., "Physical Simulation of Rocket Exhaust Aerodynamics Using Heated Ethane: Conceptual Foundations", NASA TM 2019-220446, JUN 2019.

[6] Rao, G.V.R., "Exhaust Nozzle Contour for Optimum Thrust", Journal of Jet Propulsion, Vol. 28, No. 6, p. 377-382, JUN 1958.

[7] Rao, G.V.R., "Approximation of Optimum Thrust Nozzle Contour," ARS Journal, Vol. 30, No. 6, p. 561, JUN 1960.

[8] Gordon, S., and McBride, B., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications", NASA RP-1311, OCT 1994.

[9] Luke, E., and George, T., "Loci: A Rule-Based Framework for Parallel Multidisciplinary Simulation Synthesis," Journal of Functional Programming, Volume 15, Issue 03, 2005, pp. 477-502.

[10] Luke, E. A., Tong, X-L., Wu, J., Tang, L., and Cinnella, P., "CHEM: A Chemically Reacting Flow Solver for Generalized Grids", AIAA 2003.