NASA Technical Memorandum 2019-220446

June 2019

Physical Simulation Of Rocket Exhaust Aerodynamics Using Heated Ethane:

Conceptual Foundations

Daniel R. Jones
NASA Stennis Space Center
Stennis Space Center, Mississippi

National Aeronautics and Space Administration

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA Technical Memorandum 2019-220446

June 2019

Physical Simulation Of Rocket Exhaust Aerodynamics Using Heated Ethane:

Conceptual Foundations

Daniel R. Jones
NASA Stennis Space Center
Stennis Space Center, Mississippi

National Aeronautics and
Space Administration

ABSTRACT

Heated ethane (C_2H_6) has been proposed as an alternative to inert gases for use as a motive fluid in the experimental simulation of rocket exhaust plumes. By adjusting stagnation temperature, the isentropic exponent of ethane can be tuned to approximate those produced by common rocket propellants including hydrogen, hypergols, alcohols, and hydrocarbons. As a result, ethane can be made to follow a nozzle expansion process which is nearly identical to realistic rocket engine flow fields. Additionally, its high auto-ignition temperature and resistance to condensation enable the testing of expansion ratios much larger than conventional inert-gas testing.

NASA SSC has performed quasi-one-dimensional analyses using the Chemical Equilibrium with Applications (CEA) code as a preliminary means to compare flow fields produced by non-reacting ethane to those of reacting combustion products. A LO_2/LH_2 rocket engine operating at a chamber pressure of 5.0 MPa and a mixture ratio of 6.1 was used as an example case to demonstrate ethane's efficacy as a simulant. Errors for key similarity parameters were compared to legacy cold-flow test methods. Additional errors induced by machining tolerances and chemical impurities were also examined. Results suggest that at a 3% geometric scale and ~500 K ethane stagnation temperature, an error of less than 2.5% throughout the flow field is realistically achievable along the dimensions of Mach number, Reynolds number, pressure ratio, and isentropic exponent. The development of an experimental test bed for validation of this configuration is currently underway.

NOMENCLATURE

A	Area
a	Speed of Sound
F	Thrust
$\dot{m}$	Mass Flow Rate
M	Mach Number
P	Pressure
R	Specific Gas Constant
T	Temperature
V	Velocity
β	Oblique Shock Angle
γ	Isentropic Exponent
θ	Shock or Expansion Turning Angle
ρ	Density
μ	Dynamic Viscosity
ν	Prandtl-Meyer Function

Subscripts

E	Ethane
HF	Hot-Fire
0	Stagnation Condition
1	Condition Upstream of Shock or Expansion
2	Condition Downstream of Shock or Expansion

Superscripts

*	Choked or Throat Condition

BACKGROUND

NASA's Stennis Space Center (SSC) is the nation's largest liquid rocket engine test complex. As such, the ability to predict the aerodynamic performance of supersonic rocket diffusers is of particular interest to its engineers. Computational Fluid Dynamics (CFD) has been the tool of choice for diffuser design and analysis for over a decade, but the demands of recent test programs have pushed the envelope beyond the limits of available validation data.

Hot-fire diffuser data is almost non-existent in the public domain. Extant cold-flow data was primarily published by the Air Force's Arnold Engineering Development Complex (AEDC) in the 1960s. The AEDC report which presents its aggregate data set [Ref. 1] has been the bedrock of empirical diffuser design for the past half century, but the data itself bears little resemblance to relevant, real-world, rocket-driven flow fields. Air, nitrogen, and steam were used as the motive fluids, and each create an aerodynamic expansion process disparate from that of combustion products. To avoid data degradation due to condensation in the flow field, the nozzle expansion ratio was limited to 25 and the maximum chamber pressure was notably low as well (~0.28 MPa). Given that most rockets requiring diffuser augmentation are designed for high altitude operation and therefore substantially exceed those limits, the insufficiency of the legacy data is clear.

With the intent of maintaining the low cost, simplicity, and quick turnaround of cold-flow testing, unconventional gases were evaluated for experimental use. Carbon dioxide, propane/argon blends, propylene, propane, ethane, ethylene, and nitrous oxide were initially considered as candidate simulant gases based on their isentropic exponents at standard sea level conditions. A CEA analysis of nozzle expansion behavior for each gas was conducted to compare simulant behavior to a hot-fire rocket. None of the gases produced suitable results at ambient temperature. However, ethane and ethylene were found to be capable of matching the rocket's expansion characteristics if heated. Because ethylene needed to be only ~40 K from its auto-ignition temperature and required 2-3 times the physical scale of an ethane system to match the Reynolds number of a hot-fire test, heated ethane was selected for further analysis.

FOUNDATIONAL PRINCIPLES

The basis of ethane's unique ability to replicate hot-fire rocket flow fields lies in the variation of its specific heats with temperature. This is because the fundamental behavior of supersonic flow is governed almost entirely by the ratio of specific heats (isentropic exponent) of the gas and the particular geometry it passes through. If the temperature of ethane can be manipulated such that the isentropic exponent profile through a test article matches that of chemically reacting rocket exhaust, the other key parameters of the flow field will also match.

Though the effects of shifting chemical composition and temperature-dependent heat capacities are neglected, the standard quasi-one-dimensional isentropic relations given in NACA Report 1135 [Ref. 2] are sufficient to illustrate this principle. Mach number is an implicit function of isentropic exponent and geometry. The dependence on expansion area ratio is given in (1), and the dependence on Prandtl-Meyer expansion angle in (2) and (3). Because pressure ratio (4), temperature ratio (5), and density ratio (6) are all solely dependent on Mach number and isentropic exponent, they are also strictly functions of isentropic exponent and geometry.

$$\frac{A}{A^*} = \left[\frac{1}{M}\right]\left[\frac{1+\frac{\gamma-1}{2}M^2}{\frac{\gamma+1}{2}}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

$$\theta = \nu(M_2) - \nu(M_1) \tag{2}$$

$$\nu(M)=\sqrt{\frac{\gamma+1}{\gamma-1}}\tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}[M^2-1]}-\tan^{-1}\sqrt{M^2-1} \quad (3)$$

$$\frac{P_0}{P}=\left[1+\frac{\gamma-1}{2}M^2\right]^{\frac{\gamma}{\gamma-1}} \quad (4)$$

$$\frac{T_0}{T}=1+\frac{\gamma-1}{2}M^2 \quad (5)$$

$$\frac{\rho_0}{\rho}=\left[1+\frac{\gamma-1}{2}M^2\right]^{\frac{1}{\gamma-1}} \quad (6)$$

The same is true of the equivalent normal and oblique shock relations, with the key geometric parameter being flow deflection angle. This means that both shock angles (7) and shock losses (8,9) are also replicable by temperature-tuned ethane.

$$\tan[\theta]=2\cot[\beta]\left[\frac{M_1^2\sin^2(\beta)-1}{M_1^2(\gamma+\cos(2\beta))+2}\right] \quad (7)$$

$$\frac{P_{0_2}}{P_{0_1}}=\left[\frac{P_{0_2}}{P_2}\right]\left[\frac{P_2}{P_1}\right]\left[\frac{P_1}{P_{0_1}}\right] \quad (8)$$

$$\text{where } \frac{P_2}{P_1}=1+\frac{2\gamma}{\gamma+1}[M_1^2-1] \quad (9)$$

Algebraic rearrangement of the ideal gas, speed of sound, and mass flow rate equations (10) shows that momentum flux is also a pure function of geometry and isentropic exponent via pressure and Mach number (11). Because ethane is able to produce the same pressure and momentum forces through a nozzle geometry, the resultant thrust is equivalent to a hot-fire test through that same geometry.

$$P=\rho RT, \quad a=\sqrt{\gamma RT}, \quad \dot{m}=\rho VA \quad (10)$$

$$\frac{\dot{m}V}{A}=\left[\frac{P}{RT}\right][M\sqrt{\gamma RT}]^2=\gamma PM^2 \quad (11)$$

Ethane's molecular weight is substantially higher than typical of rocket propellant combustion products. This means that at any point in the flow field where its pressure and Mach number match hot-fire, its density will be higher and velocity will be lower due to the lower specific gas constant. Combined with differences in viscosity, this leads to another desirable effect: a reduced geometric scale for Reynolds number similitude. The ideal scale factor can be calculated using equation (12).

$$\text{Ideal Scale Factor}=\left[\frac{\rho_{HF}}{\rho_E}\right]\left[\frac{V_{HF}}{V_E}\right]\left[\frac{\mu_E}{\mu_{HF}}\right] \quad (12)$$

PERFORMANCE AS A SIMULANT

The performance of ethane as a simulant gas will vary from case to case depending primarily on the specific propellant combination being represented. As an example application, consider a LO_2/LH_2 rocket engine with a 115 mm nozzle throat and 100:1 expansion ratio operating at a chamber pressure of 5.0 MPa with a mixture ratio of 6.1. The objective is to perform non-reactive testing of the nozzle at subscale and replicate its internal flow field.

Fig. 1 shows the variation of the hot-fire isentropic exponent through the nozzle, as computed by CEA [Ref. 3]. The same is also plotted for ethane using an identical chamber pressure and a stagnation temperature range of 480 to 530 K. Ethane's 490 K and 500 K profiles closely match the rocket's at lower expansion ratios, while the 520 and 530 K profiles are closer at high expansion ratios. Minimization of isentropic exponent error is required to obtain the best approximation. Average isentropic exponent error over the full nozzle expansion process can be plotted as a function of ethane stagnation temperature, as seen in Fig. 2. Minimum error occurs at a temperature of ~505 K, which is taken as the nominal setpoint for testing.

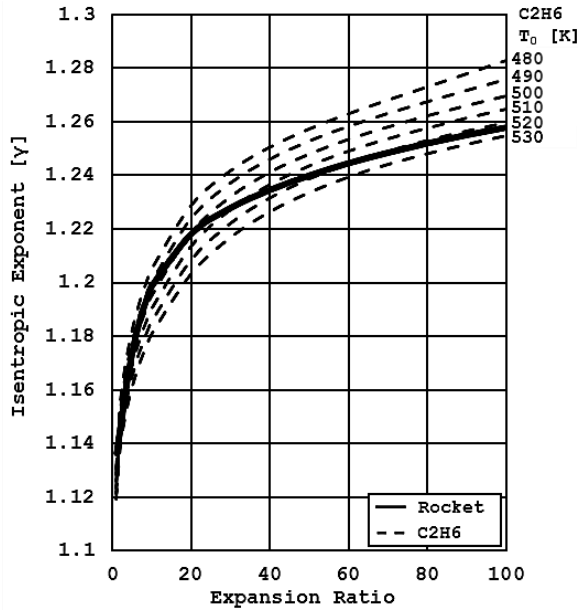

Figure 1 – Comparison of rocket and ethane isentropic exponent profiles through a 100:1 nozzle expansion process.

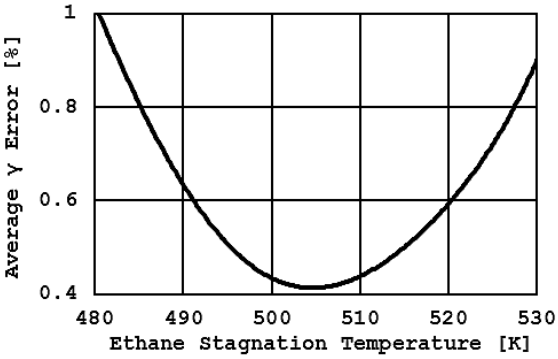

Figure 2 – Average isentropic exponent error through the nozzle as a function of ethane stagnation temperature.

To check for condensation, ethane's expansion process is compared to its phase diagram in pressure-temperature space (Fig. 3). The flow does not reach saturation within the nozzle. Plots of ethane-driven Mach number, pressure, thrust, and temperature ratio error profiles vs. hot-fire shown as a function of expansion ratio in Fig. 4. Notably, all errors except temperature ratio are within ±1%. Fig. 4 also gives the ideal scale factor for Reynolds number similitude. The density of ethane is ~15X that of the combustion products, and its speed of sound and viscosity are ~1/4 and ~1/10, respectively. This means optimum Reynolds scaling can be achieved at a 2.75-3.25% geometric scale, depending on the expansion ratio of

greatest interest. Assuming the nozzle exit plane fits that description, the appropriate 2.75% scale gives a nozzle throat diameter of 3.175 mm which passes .066 kg/s of ethane.

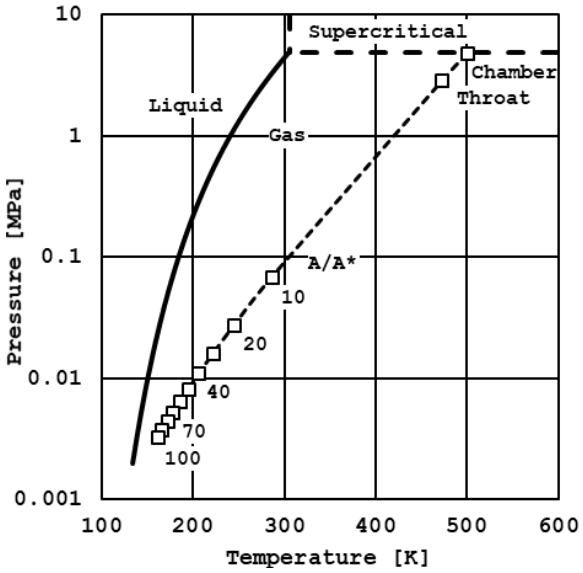

Figure 3 – Ethane's expansion process through the nozzle compared to its phase diagram.

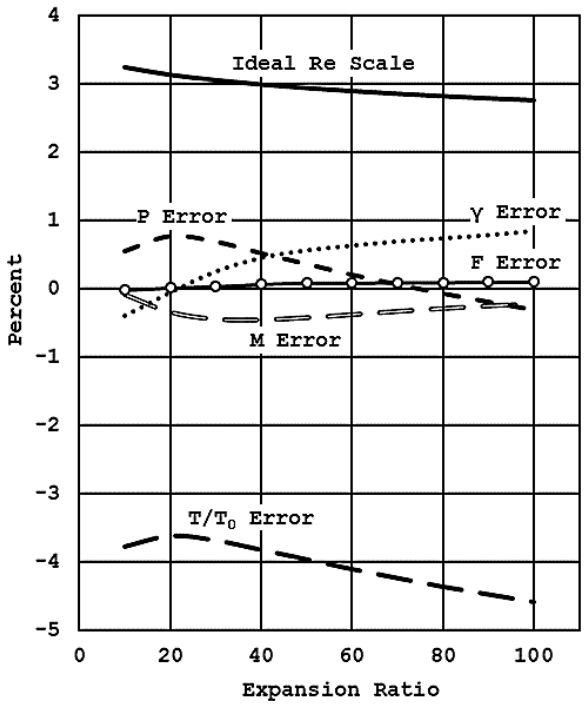

Figure 4 – Ideal Reynolds scale of the example ethane test article and error profiles of key aerodynamic parameters vs. hot-fire.

To compare ethane's aerodynamic errors to legacy cold-flow testing, steam and nitrogen are considered under optimum conditions for each, assuming the same stagnation temperature (505 K) is achievable. Nitrogen condensation can be avoided by testing at a lower chamber pressure (0.5 MPa for this case). However, this comes with the added complication of testing against a reduced backpressure to maintain the desired pressure ratio across the nozzle. Steam reaches saturation at much higher temperatures so condensation is inevitable through the expansion process, though a higher degree of initial superheat can reduce the magnitude. As such, an additional case with a steam stagnation temperature of 750 K was considered. Fig. 5 shows the pressure ratio error of each simulant fluid vs. LO_2/LH_2 combustion products, as well as steam's mass condensation profiles. Superheated steam has an isentropic exponent higher than that of a rocket plume. However, that relationship is reversed when the expanding flow reaches saturation at low area ratios, making the steam less sensitive than combustion products to further changes in area. As a result, the steam-driven pressure is higher than that driven by rocket exhaust over the majority of the expansion process. Conversely, nitrogen's isentropic exponent is significantly higher than that of rocket exhaust which makes it more sensitive to area changes and produces lower pressures for the same geometry. Air was not plotted because it produces an error profile nearly identical to nitrogen's. The relatively minimal pressure error produced by ethane shows its superiority as a simulant if properly tuned to the application.

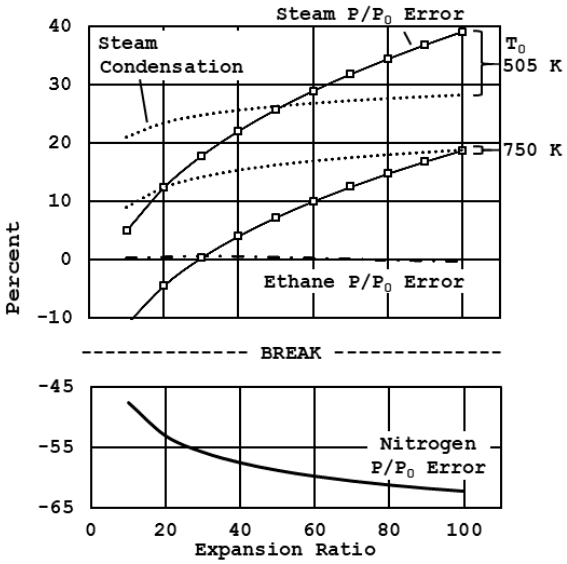

Figure 5 – Comparison of Simulant Gas Errors vs. LO_2/LH_2 Hot-Fire, P_0 = 5 MPa, O/F=6.1

Despite ethane's baseline aerodynamic error being extremely low, there are other potential sources of error that arise from its practical application. Because the geometric scale of the test article is so small, the errors induced by machining tolerances are on the order of those produced by its isentropic exponent profile. Fig. 6 shows the effect of tolerance specifications on ethane's pressure error for the example system. The percentages given are in addition to the errors shown in Fig. 4.

Another consideration is the quality of gas purchased for testing. High purity ethane (>99.9%) can be significantly more expensive than ethane containing 1% to 2.5% other gases. The additional errors induced by the most prominent contaminants of ethane (by mass fraction), nitrogen and methane, are shown in Fig. 7 for purity levels commonly offered by gas supply companies. These errors are also in addition to those in Fig. 4.

The cumulative effect of independent error sources can be determined by adding the components in quadrature [Ref. 4]. Assuming 98.5% purity ethane contaminated by methane and a +0.025 mm / -0.0 mm tolerance specification, the maximum cumulative

pressure error vs. hot-fire would be ~2.5%, occurring at the nozzle exit.

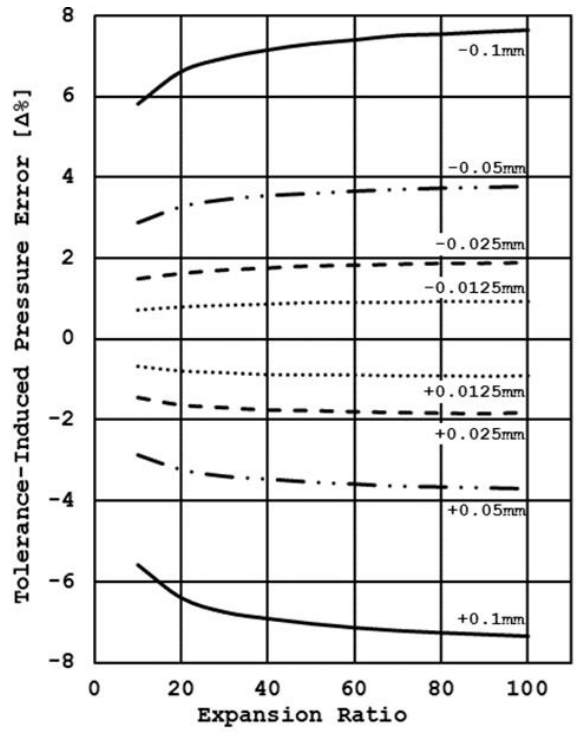

Figure 6 – Effect of machining tolerances on aerodynamic performance.

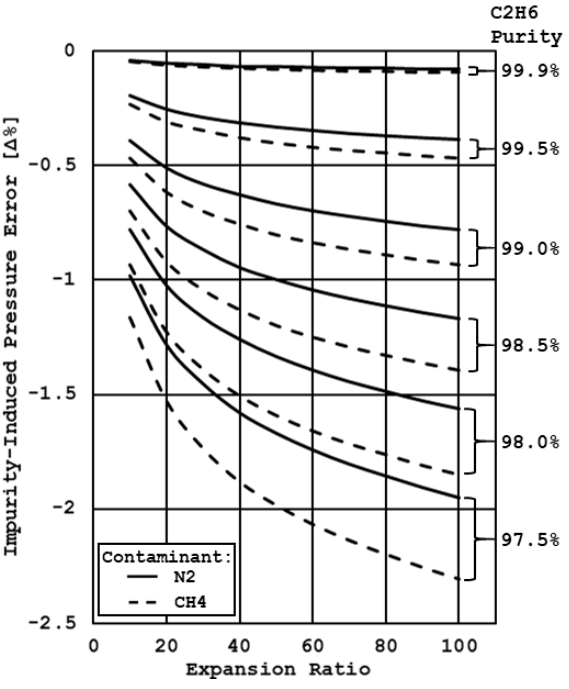

Figure 7 – Effect of ethane purity on aerodynamic performance.

LIMITATIONS AND APPLICATIONS

Two physical processes provide the bounds of ethane's operational envelope as a simulant gas: condensation on the low end of the temperature range and chemical reactivity on the high end.

Condensation can occur during the nozzle expansion process as the temperature and pressure. Fig. 8 plots the results of a CEA analysis which determined the quasi-1D nozzle expansion ratio above which condensation occurs for a variety of stagnation temperatures and pressures. Ethane condenses more readily at higher pressures and lower temperatures but realistic upper-stage nozzles remain testable.

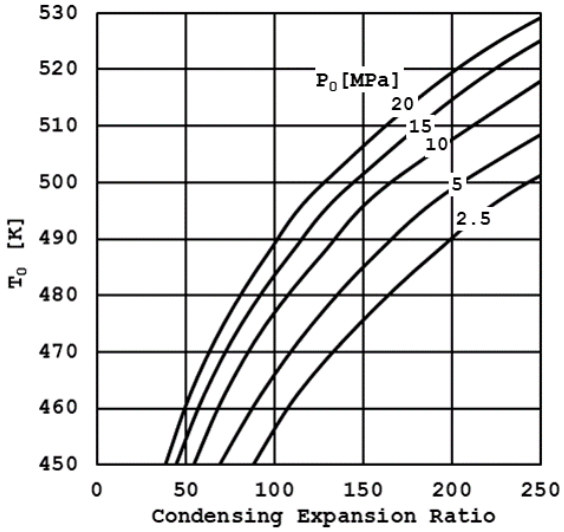

Figure 8 – Quasi-1D condensation potential vs. stagnation temperature and pressure

The primary inconvenience of using ethane as a motive fluid is its chemical reactivity. It has an auto-ignition temperature of 788 K and a flammability range of 3 to 12.5% by volume in air [Ref. 5]. Though relatively small flow rates are required for testing due to the ~3% geometric scale, the potential for ignition must be considered when designing a test bed. Additionally, thermal decomposition can begin to affect aerodynamic accuracy below the auto-ignition temperature. Because it is easy to imagine a test-day scenario in which the ethane is heated and not immediately flowed through the test article, a Cantera [Ref. 6] analysis was performed to determine the dependency of pyrolysis on temperature, pressure, and residence time using the Gas Research Institute's GRI-Mech 3.0 hydrocarbon reaction mechanism [Ref. 7]. Fig. 9 shows the results. The amount of decomposition produced by temperatures at or below 725 K is not a practical concern, as only ~0.1% of the ethane mass is affected. However, the affected mass fraction increases to ~1% at 800 K, with ethylene (C_2H_4) being the dominant byproduct. At that level, the aerodynamic errors induced by the decomposition products are on the order of other contributors (tolerances, purity, etc.) and must be accounted for. There is little pressure dependency across the 4 to 20 MPa range.

With the upper and lower temperature limits anchoring the tunable range of ethane's isentropic exponent, it becomes possible to determine the concept's envelope of applicability. Ethane's bounding isentropic exponent profiles are plotted in Fig. 10 and compared to profiles produced by common rocket propellant combinations. This shows that ethane can be potentially used to replicate a wide variety of rockets, with fuels spanning alcohols, hydrocarbons, hydrogen, and hypergols.

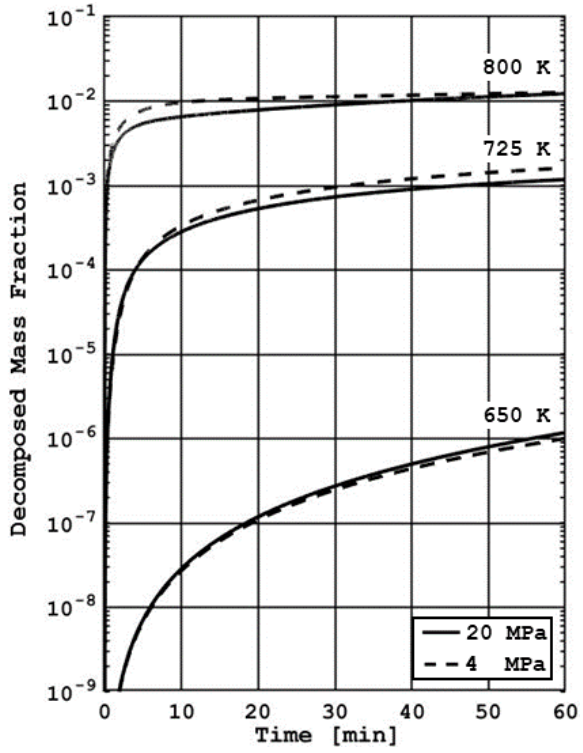

Figure 9 – Temporal variance of ethane's pyrolytic products at elevated temperatures.

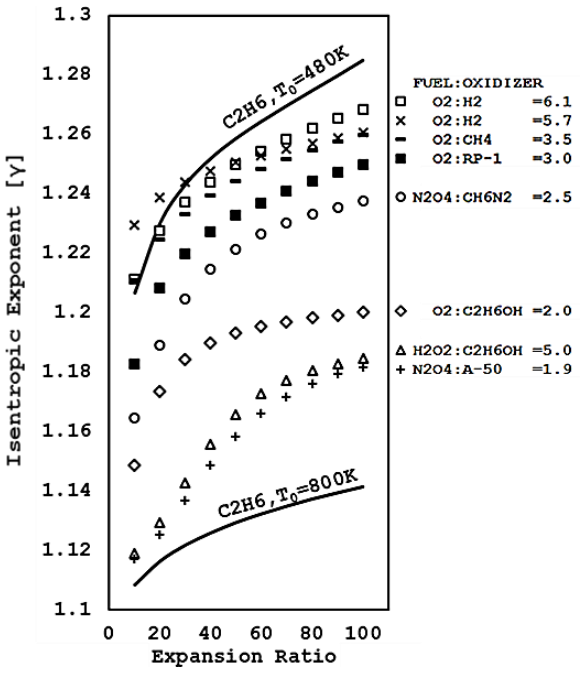

Figure 10 – Operational envelope of ethane's isentropic exponent profiles compared to common rocket propellant combinations at P_0 = 15 MPa.

FUTURE WORK

SSC is currently overseeing the design and build-up of a portable test bed capable of delivering ethane to a test article at specified temperature and pressure conditions. Multiple test articles with known hot-fire aerodynamics will be employed as validation cases: an upper stage nozzle coupled with three passive diffusers, an SSME-equivalent nozzle in a free-plume configuration, and four supersonic retropropulsion nozzles coupled with passive diffusers. Upon completion of testing, a follow-up paper detailing the concept's validation will be published.

CONCLUSIONS

Conceptually, heated ethane appears to be a promising motive fluid for the physical simulation of rocket plume aerodynamics, offering a wider range of operability and significantly improved accuracy compared to legacy cold-flow techniques. It is inexpensive, non-toxic, has a high auto-ignition temperature, and does not thermally decompose or condense over the temperature and pressure ranges most useful for replicating rocket flow fields. Additionally, the small geometric scale required to match Reynolds number lends itself to lean, lab-scale hardware. An initial series of testing has been planned for validation of the concept described in this paper.

REFERENCES

[1] Taylor, D., and Toline, F., "Summary of Exhaust Gas Ejector - Diffuser Research", AEDC-TR-68-84, OCT 1968.

[2] Ames Research Staff, "Equations, Tables, and Charts for Compressible Flow," NACA-TR-1135, JAN 1953.

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

[4] Taylor, J. "An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements", University Science Books, 1982.

[5] Ethane; Safety Data Sheet P-4592 (Online), Praxair Incorporated, https://www.praxair.com/, JAN 1979.

[6] Goodwin, R., Speth, H., Moffat, K., and Weber, B., "Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes" https://www.cantera.org, 2018. Version 2.4.0.

[7] GRI-Mech 3.0, The Gas Research Institute, http://www.me.berkeley.edu/gri_mech/.