Public Data for this TechPort entry

High energy density additives for Hybrid Fuel Rockets to Improve Performance and Enhance Safety

Center Innovation Fund: ARC CIF Program

- Public Data

Project Introduction

Abstract

We propose a conceptual study of prototype strained hydrocarbon molecules as high energy density additives for hybrid rocket fuels to boost the performance of these rockets without compromising safety and reliability. Use of these additives could extend the range of applications for which hybrid rockets become an attractive alternative to conventional solid or liquid fuel rockets.

The objectives of the study were to confirm and quantify the high enthalpy of these strained molecules and to assess improvement in rocket performance that would be expected if these additives were blended with conventional fuels. We confirmed the chemical properties (including enthalpy) of these additives. However, the predicted improvement in rocket performance was too small to make this a useful strategy for boosting hybrid rocket performance.

Detailed Description

Hybrid rockets use a solid fuel with a liquid or gaseous oxidizer. They have advantages over solid fuel rockets for certain space applications because the solid fuel component is more stable than a combined solid fuel and oxidizer, and have advantages over liquid fuel rockets because the fuel does not require cryogenic storage or pumping and the burn rate can be controlled by regulating the flow of oxidizer. Ideal fuels should exhibit a fast regression rate, high density and good mechanical stability (so it will not break apart during burning). A current project at ARC is to evaluate hybrid rockets comprised of solid paraffin fuel and cryogenic nitrous oxide and LOX oxidizer and has shown that higher regression rates are needed. Strained cyclic hydrocarbons have positive enthalpy and can be blended with paraffins to make fuels for hybrid rockets, but to be effective the resulting solid must have physical and mechanical characteristics at least comparable to the pure paraffin fuels. The stable hydrocarbon molecules with the highest strain energy are comprised of triangular rings of carbon atoms (cyclopropane), but these are gases at normal temperatures and pressures. Recently, chemists have synthesized molecules (called ivyanes, shown in Figure 1) containing multiple cyclopropane rings bonded together. We propose investigating blends of ivyanes and paraffins to determine their
thermochemical and physical properties. We will first carry out simulations to predict the enthalpy, density and stability of these blends using first principles chemistry and physics methods. Previously, first principles calculations by two of us (Jaffe and Zehe, J. Organic Chem. 2010, 75, 4387) demonstrated thermochemical properties can be determined to an accuracy of 2 kJ/mol for hydrocarbon molecules containing 10-20 carbon atoms. In the second phase, the density, melting temperature and heat of sublimation of solid ivyanes and the blends will be determined from molecular dynamics simulations.

**Project Library (conference paper)**


**Technologies Within this Project**

This technology is categorized as a hardware component or part for other applications

**Technology Details: High energy density additives for Hybrid Fuel Rockets to Improve Performance and Enhance Safety**

Hybrid rockets use a solid fuel with a liquid or gaseous oxidizer. They have advantages over solid fuel rockets for certain space applications because the solid fuel component is more stable than a combined solid fuel and oxidizer, and have advantages over liquid fuel rockets because the fuel does not require cryogenic storage or pumping and the burn rate can be controlled by regulating the flow of oxidizer. Ideal fuels should exhibit a fast regression rate, high density and good mechanical stability (so it will not break apart during burning). A current project at ARC is to evaluate hybrid rockets comprised of solid paraffin fuel and cryogenic nitrous oxide and LOX oxidizer and has shown that higher regression rates are needed. Strained cyclic hydrocarbons have positive enthalpy and can be blended with paraffins to make fuels for hybrid rockets, but to be effective the resulting solid must have physical and mechanical characteristics at least comparable to the pure paraffin fuels. The stable hydrocarbon molecules with the highest strain energy are comprised of triangular rings of carbon atoms (cyclopropane), but these are gases at normal temperatures and pressures. Recently, chemists have synthesized molecules (called ivyanes, shown in Figure 1) containing multiple cyclopropane rings bonded together. We propose investigating blends of ivyanes and paraffins to determine their thermochemical and physical properties. We will first carry out simulations to predict the enthalpy, density and stability of these blends using first principles chemistry and physics methods. Previously, first principles calculations by two of us (Jaffe and Zehe, J. Organic
Chem. 2010, 75, 4387) demonstrated thermochemical properties can be determined to an accuracy of 2 kJ/mol for hydrocarbon molecules containing 10-20 carbon atoms. In the second phase, the density, melting temperature and heat of sublimation of solid ivyanes and the blends will be determined from molecular dynamics simulations.

Capabilities provided:

Use of hydrocarbon additives could solve problems of fuel pellet break up encountered with aluminum or lithium additives without sacrificing higher regression rates (burn rates), and lead to enhanced safety and lower cost compared to solid and liquid rocket propulsion systems.

Potential applications:

Mars sample return, in-space propulsion, upper-stage launch vehicle

Anticipated Benefits

Benefits to NASA funded missions

Any NASA funded mission that is using hybrid fuel rocket technology can benefit from this technology.

U.S. Locations Working on this Project

<table>
<thead>
<tr>
<th>NASA Organizations Performing Work</th>
<th>Role</th>
<th>Location</th>
</tr>
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<tr>
<td>• Ames Research Center (ARC)</td>
<td>Lead Center</td>
<td>Moffett Field, CA</td>
</tr>
<tr>
<td>• Ames Research Center (ARC)</td>
<td>Supporting Center</td>
<td>Moffett Field, CA</td>
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<tr>
<td>• Glenn Research Center (GRC)</td>
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U.S. States with Work:

U.S. States and Territories with Work on this Project

California

Share or Follow this Project

Organizational Responsibility

Responsible Mission Directorate:
Space Technology Mission Directorate (STMD)

**Lead Center:**
Ames Research Center (ARC)

**Responsible Program:**
Center Innovation Fund: ARC CIF Program

**Project Management**

**Program Executive:**
- Minoo Dastoor

**Program Manager:**
- John Hines

**Project Manager:**
- Richard Jaffe

**Principal Investigator:**
- Richard Jaffe

**Project Technology Areas**

**Primary:**
- Launch Propulsion Systems (TA01)
  - Unconventional / Other Propulsion Systems (TA01.5)

**Secondary:**
- In-Space Propulsion Technologies (TA02)

**Project Duration**

**Start Date:** Aug 2011
**End Date:** Jan 2012

**Project Technology Maturity**
Characterization and Evaluation of High Energy Hydrocarbon Additives for Paraffin-Fuel Hybrid Rockets

Richard L. Jaffe,1 Arif Karabeyoglu,2 Brian Evans,3 Gregory G. Zilliac,4 and Michael S. Sherburn5

Highly strained hydrocarbons called ivyanes are evaluated as a potential additive to boost the burn rate and $I_p$ for liquefying paraffin hybrid rockets. Ivyanes, which consist of cyclopropane rings bonded together, were first prepared in 2011 and have promise as a High Energy Density Material (HEDM) for propulsion and combustion applications. Differential Scanning Calorimetry (DSC) measurements were carried out on samples of ivyane and an ivyane-paraffin blend to measure phase changes and thermal stability. Quantum chemistry calculations were carried out using the G3MP2/B3LYP method to predict heats of formation and combustion for gas phase ivyanes. For validation purposes, calculations were also carried out for normal alkanes. Chemical equilibrium analysis was used to estimate the performance of ivyanes relative to paraffin for typical rocket engine scenarios. In addition, thermochemical properties of some plausible chemically modified ivyanes were modeled to determine if they would improve rocket engine performance.

1. Introduction.

Hybrid rockets utilizing solid fuel and liquid or gaseous oxidizers have certain advantages over solid and liquid rockets, for example the fuel is stable and the oxidizer can be throttled to control the burn rate and even stop and restart the engine. Recent work at NASA Ames Research Center has focused on developing a liquefying paraffin fuel for hybrid rockets. To this end, tests have been carried out using a prototype engine named Peregrine1,2. Although the performance of this engine is promising, on-going work is directed at enhancing the burn rate and specific impulse ($I_p$). One avenue of research is to evaluate the potential of using a highly energetic molecular additive as a fuel component.

For more than 40 years the rocket design community has been searching for a way to boost the performance of rocket engines. In the Soviet Union scientists came up with a liquid hydrocarbon fuel called syntin3,4 that they started using in the second stage engine of the Soyuz-U2 rocket. It has the chemical proper chemical name 1-methyl-1,2-dicyclopropylcyclopropane, $C_{10}H_{16}$, and is comprised of three cyclopropyl rings joined

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4 Research Scientist, Experimental Aero-Physics Branch, NASA Ames Research Center, Moffett Field, CA 94035
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together (Fig. 1). It has a positive enthalpy of formation (+199.2 kJ/mol (gas) and +151.9 kJ/mol (liq.)) and an estimated strain energy (from the cyclopropyl rings) of 313.6 kJ/mol. After the demise of the Soviet Union production of syntin was stopped because it was too expensive to produce for the amount of performance improvement as a rocket fuel.

In the United States, NASA and the Air Force had their own programs to develop energetic rocket fuels or fuel additives. The Air Force Office of Scientific Research (AFOSR) program begun in 1987 was called HEDM (High Energy Density Materials) and was at its peak in the mid 1990s. It supported exploratory research to identify candidate fuel components. That program studied strained hydrocarbons like cubane (C₈H₈), which has one carbon at each vertex of a cube, and clusters of nitrogen atoms such as tetrahedral N₄, N³⁺ and N⁵⁻. Cubane has very high strain energy because the angles between adjacent C-C bonds are compressed to 90° from the optimal value of 109.5° in tetrahedral carbon. The strain energy of molecules like cubane translates into a higher heat of combustion when the fuel is burned. Similarly, when heated to their decomposition temperature, nitrogen clusters are converted to diatomic nitrogen, releasing considerable heat. Much of the research supported by HEDM was based on modeling and simulation. In practice it proved very difficult and expensive to actually synthesize the proposed molecules and the program was terminated.

One recently synthesized family of hydrocarbons based on cyclopropyl rings is called ivyanes. Cyclopropane (C₃H₆), has an equilateral triangle geometry with 60° angles between adjacent C-C bonds and one of the largest strain energies of all known hydrocarbons. Ivyanes (shown in Figure 2) have multiple cyclopropyl rings and are ideal HEDM candidates. They are especially attractive as additives for liquid kerosene and solid paraffin fueled rockets, because they have similar chemical compositions to these fuels, which should mean that these components would form stable blends. An added benefit is that the ivyane synthesis is simple compared to most other HEDM candidates, thereby reducing the cost of manufacture.
In the present study, we are interested in potential additives for the Peregrine rocket engine, and are therefore interested in additives for solid paraffin. To be effective, a potential additive should have the following properties: (1) high positive formation enthalpy ($\Delta_f H^\circ$), (2) melting temperature similar to that of paraffin, (3) stoichiometry such that the ratio of hydrogen to carbon atoms (H/C) is as high as possible in order to maximize Isp, (4) complete miscibility with paraffin, and (5) low cost. The specific impulse is a measure of rocket engine efficiency$^1$ and has units of seconds. It is the ratio of the thrust generated by exhaust gases to the product of the gravitational constant and the mass flow rate in the exhaust. Having a faster fuel burn rate and lower average molecular weight for the exhaust gases increases Isp. When hydrocarbon fuels are burned, all the carbon atoms are converted into CO$_2$ (44 g/mol) and all the hydrogen atoms are converted into H$_2$O (18 g/mol). Thus, a higher H/C ratio in the fuel results in a lower average molecular weight and higher exit velocity of the exhaust gases.

The paraffin used for the Peregrine project is a mixture of unbranched alkane chains with an average chain length of 32 (C$_{32}$H$_{66}$), a melt temperature of 69 C and $\Delta_f H^\circ(s) = -933$ kJ/mol$^{11}$. Ivyanes have been prepared as chains with up to eight cyclopropane rings and are sketched in Figure 2 (n in the notation [n]ivyane, refers to the number of cyclopropane rings). [7]- and [8]ivyane (C$_{21}$H$_{30}$ and C$_{24}$H$_{34}$, respectively) are solids and ivyanes with lower [n] are liquids at room temperature. The heat of combustion has been determined for [6]ivyane(l): $\Delta_c H^\circ = -12,300 \pm 600$ kJ/mol$^9$ or $-50.8$ kJ/g, which is equivalent to $\Delta_f H^\circ = +1500 \pm 600$ kJ/mol. In comparison, paraffin has a heat of combustion of $-21,092$ kJ/mol or 46.9 kJ/g. According to these data, [6]ivyane releases ~8% more energy per gram than paraffin when burned. On the other hand, the H/C ratio is 2.06 for paraffin compared to 1.41-1.44 for ivyanes. For overall performance, higher energy release favors ivyanes, but the H/C ratio favors paraffin. Isp is dependent on both.

The present paper describes the characterization of ivyanes and an assessment of their suitability for use in paraffin-fuel hybrid rockets. For this project we obtained small samples of [6]- and [7]ivyane from the Sherburn research group at the Australian National University, Canberra, Australia, where it was first synthesized. In the next section we describe the physical properties of ivyanes, including data obtained from analysis of the samples we received$^9$. In Section 3 we discuss computational studies of ivyanes to confirm and predict their heats of combustion and formation. In addition we discuss variations of the ivyane chemical structure that might lead to improved performance as a rocket fuel additive. In Section 4 we present an assessment of the performance of ivyane and the proposed variations in an idealized rocket engine using a thermochemical equilibrium model and comment on the prospects for this family of strained hydrocarbons as a rocket fuel or fuel additive.

Figure 2. Schematic drawings of two ivyanes. Each vertex of a triangle represents one carbon atom and the lines represent C-C bonds. Two hydrogen atoms (not shown) are bonded to each carbon atom except for the backbone atoms (i.e., where the triangular rings are linked together).
2. Physical Characteristics of Ivyanes

Sherburn and coworkers, first reported the synthesis of a class of 1,1-oligocyclopropanes, called ivyanes, in 2011\(^9\). These molecules have numerous cyclopropyl groups bonded together like a string of pearls. The 60° angle between adjacent carbon-carbon bonds in cyclopropyl imparts high strain energy to the ring, as the optimal (i.e., strain free) angle between carbon-carbon bonds is 109.5°. Ivyane chains with up to 8 cyclopropyl rings have been prepared. Chains with up to 6 cyclopropyl groups are liquid at room temperature and those with 7 or more are waxy solids. In Sherburn’s nomenclature \([n]\)ivyane refers to a molecule with \(n\) cyclopropyl groups (empirical formula \(C_{3n}H_{4n+2}\)). The ivyanes were prepared in one step from another class of molecules called \([n]\)dendralenes\(^{12}\) shown in Figure 3. Each \([n]\)dendralene has \(n\) carbon-carbon double bonds that can be converted into cyclopropyl rings. Dendralenes are easy to synthesize with up to 6 double bonds, but longer ones have been prepared as well. Sherburn reported some of the physical properties of the \([n]\)ivyanes in the supplemental material that accompanied the original publication\(^9\). Included are bomb calorimetry measurements of the heat of combustion of \([6]\)ivyane that show it to have a standard enthalpy of combustion, \(\Delta H^\circ\), equal to \(-12,300 \pm 600\) kJ/mol, which is equivalent to \(-50.8 \) kJ/g. This result makes \([6]\)ivyane one of the most highly strained hydrocarbons known.

![Figure 3. Schematic drawing of [7]dendralene. The double lines represent the carbon-carbon double bonds. The details of the figure are similar to those in Figures 1 and 2 except that all hydrogen atoms are shown.](image)

The goals of the experimental characterization are to determine the melt and boiling temperatures, density, heats of fusion and vaporization and thermal stability of the pure samples. To assess their miscibility with paraffin, a small sample of a 1:1 paraffin-[7]ivyane blend (by weight) has been prepared by melting the solid mixture followed by cooling to room temperature.

Differential scanning calorimetry (DSC)\(^{13}\) was carried out for samples of the pure components and the blend. DSC measures the heat flow into and out of a sample as the temperature is raised and then lowered at a controlled rate (in this case \(\pm 2\) C/minute). In the absence of phase changes or chemical reactions, the amount of heat needed to raise the temperature of the sample is small and proportional to the heat capacity. When the sample melts or vaporizes additional heat is required to overcome the enthalpy of fusion or vaporization. This is an endothermic change in the sample and shows up as a dip in the heat flow. When the sample undergoes oxidation or thermal decomposition heat is released and the heat flow curve has a peak. DSC measurements require only \(\sim 10\) mg
samples. Figures 4 and 5 show the DSC results for [7]ivyane and the 1:1P-I blend. The deep feature at ~ 50 C in both figures is the melt transition that occurs as the samples are heated. In Figure 4a and 5 an open sample container was used and the sample reacted with atmospheric oxygen when the temperature was increased above 250 C. In Figure 4b and 4c the sample was in a closed container and the high temperature peaks (Figure 4c) are indicative of non-oxidative decomposition. No boiling transition was observed. The fact that the melt transitions for [7]ivyane and the 1:1 P-I blend are similar suggests that the components are well mixed in the blend. However, the melt transition occurs over a broader temperature range in the blend, because the melt temperature of [7]ivyane is around 20 C lower than pure paraffin (shown in Figure 6). The phase change energy for [7]ivyane and the blend (i.e., heat of fusion) were determined to be 48.6 J/g and 123.1 J/g, respectively, which is close to the average of [7]ivyane and pure paraffin heats of fusion (0.5(48.6+216.1) = 132.3 J/g) as expected for a 1:1 mixture. The DSC results for [6]ivyane using a closed container did not show any sign of a phase transition for the temperature range -50 C to 300 C. That test also showed thermal decomposition occurring at temperatures above 300 C. After the DSC runs the containers were opened and examined, revealing changes in appearance of the ivyane samples.

In addition, the density of [6]ivyane was measured using a sample container with a volume of 0.0562 cm³. Mass was added to the container until the liquid level was even with the top of the container. The container and sample were then weighed on a scale with precision to 0.0001 g. An average density was calculated based on 4 measurements. The sample masses were 0.0557 g, 0.0547 g, 0.0559 g, and 0.0555 g, which relate to densities of 0.9915 g/cm³, 0.9737 g/cm³, 0.9950 g/cm³, and 0.9879 g/cm³. The average density was then 0.9870 g/cm³.

3. Modeling of Ivyanes Thermochemical Properties

Modeling of individual gas-phase ivyane molecules is carried out to estimate heats of combustion and formation. We use quantum chemistry methods that involve solving the electronic Schrodinger equation to obtain the ground state electronic energy of a molecule with fixed nuclei. A general description of the approach is given in reference 14. Since the early 1990s, a successively more accurate series of composite methods have been developed with the goal of using quantum chemistry calculations to predict the thermochemical properties of small to medium sized molecules. In these methods, the molecular geometry and harmonic vibration frequencies are first determined at a relatively low level of accuracy and then successive calculations are carried out at that geometry to ascertain the affect of using larger atomic orbital basis set expansions and better treatments of electron correlation. In addition, an empirical correction term is applied to compensate for remaining deficiencies in the method. This empirical correction is constructed to minimize the average error of computed properties such as standard heat of formation, ionization potential and dipole moment for a large test set of small molecules. The first method was called G2 [15] and could only be applied to molecules with fewer than 10-15 atoms (including hydrogen). The next method, called G3 [16], was further adapted to use a simpler treatment of electron correlation (G3MP2) and finally to utilize density functional theory (DFT) for the initial geometry and harmonic frequency calculation. That composite method is called G3MP2/B3LYP [18] and uses the hybrid DFT functional developed by Becke [19] for balancing the effects of
electron exchange and correlation. Values of standard heats of formation for the 299-
molecule test set computed using the G3MP2//B3LYP method have a 5.2 kJ/mol mean
absolute deviation with experimental data. This method has been shown to work well for
the jet fuel additive JP10 (C_{10}H_{16}), which is a strained polycyclic hydrocarbon^{20}. For the
current study we use the G3MP2//B3LYP method as implemented in the Gaussian
software package^{21}.

The enthalpy calculations are straightforward, but in order to obtain standard
heats of formation from the total molecular energies one must assume a model chemistry.
This is a reaction that relates the energy of a target molecule to other atomic and
molecular species with known heats of formation^{22,23}. Several possibilities are illustrated
for [5]ivyane (C_{15}H_{22}):

\[
\begin{align*}
\text{[5]ivyane (g) + 20.5 O}_2 & \rightarrow 15 \text{ CO}_2 (g) + 11 \text{ H}_2\text{O (l)} \quad \text{`combustion'} \\
\text{[5]ivyane (g)} & \rightarrow 15 \text{ C (s) +11 H}_2 (g) \quad \text{`atomization (ATO)'} \\
\text{[5]ivyane (g) + 23 CH}_4 (g) & \rightarrow 19 \text{ C}_2\text{H}_6 (g) \quad \text{`bond separation (BS)'} \\
\text{[5]ivyane (g) + 4 H}_2 (g) & \rightarrow 5 \text{ cyc-C}_3\text{H}_6 (g) \quad \text{`cyclopropyl conservation (CP)'} \\
\text{[5]ivyane (g) } & \rightarrow 4\text{-methyl diadamantane (g)} \quad \text{`isomerization (ISO)'} \\
\end{align*}
\]

The approach is illustrated for the combustion reaction. The heat released by this
reaction at T=298 K is:

\[
\Delta H_{\text{rxn}}(298) = 15 \text{ HCO}_2(g) + 11 \text{ H}_2\text{O(l)} - \text{H}[5]ivyane(g) - 21.5 \text{ H}_2\text{O(g)}
\]

(H_{x} signifies the enthalpy at 298 K for species x). We first compute \(\Delta H_{\text{rxn}}(298)\) by
combining the computed enthalpies of all the reactant and product species determined
using the G3MP2//B3LYP method and then equate it with the expression for \(\Delta H_{\text{rxn}}(298)\)
using standard heats of formation for all species (e.g., from the NIST Chemistry
Webbook database^{24}) except [5]ivyane, which is treated as the unknown. Previously, the
bond separation and isomerization reactions were found to work best for JP10^{20}. The
disadvantage with this method is that the errors associated with all the other reactant and
product molecules are additive. For larger molecules, these errors in the reference species
energies (e.g., CH_{4}, C_{2}H_{6} for the bond separation case) are amplified by the large
coefficients needed to balance the reaction. A better approach is to use the energy
difference between the target molecule and an isomer whose heat of formation is known.
Fortunately there are isomers of [3]-[5]ivyane with known heats of formation in the NIST
database^{24}. For example, [5]ivyane and 4-methyl diadamantane have the same
stoichiometry (C_{15}H_{32}). The calculations were carried out for [2]-[6]ivyane, but the larger
ivyane molecules are too big for this method to be practical. The results of these
calculations are given in Table 1 and in Figures 7 and 8. Note that values are given for
gas phase molecules even though these ivyanes are liquids at standard conditions (T =
298.16 K and P = 10^{5} Pa). The dashed lines are extrapolated values for larger ivyane
number based on the heat of combustion per unit weight of the ivyane molecule. Also the
correction described below for the computed standard heat of combustion has been
applied. There is also concern that the empirical correction term added to the computed
G3MP2//B3LYP energies might not be accurate for molecules that are much larger than
tany of the ones in the test set. For validation purposes calculations were also carried out for a series of normal alkanes with 4 to 20 carbon atoms. The gas phase and condensed phase standard enthalpies of formation for these molecules are also contained in the NIST database. Results for the alkanes are given in Table 2 and Figures 9-11.

Table 1. Gas phase enthalpies of combustion and formation (in kJ/mol) for the ivyane series from G3MP2//B3LYP calculations. Experimental data from NIST (reference 24).

<table>
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<tr>
<td>ΔfH°(g) ATO</td>
<td>57.15</td>
<td>138.42</td>
<td>212.09</td>
<td>289.14</td>
<td>360.28</td>
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<tr>
<td>ΔfH°(g) BS</td>
<td>56.84</td>
<td>139.37</td>
<td>214.31</td>
<td>292.63</td>
<td>365.03</td>
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<td>ΔfH°(g) CP</td>
<td>53.3</td>
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<td>53.3</td>
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<td>ΔcH°(g)</td>
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From Table 1 it is evident that the computed ΔfH°(g) based on the bond separation method and atomization reactions are comparable and for [1]- and [2] ivyane (cyclopropane and bicyclobutyl) in excellent agreement with experiment measurements. Use of the cyclopropyl conserving reaction consistently yields lower heats of formation than the other methods, and the differences are increasing with ivyane number. Determination of ΔfH°(g) from the isomerization reaction is problematic. In previous work (reference 20) this reaction gave superior results to the bond separation and atomization methods. In that case, the comparison was between JP-10 (C_{10}H_{16}) and adamantane – both are polycyclic hydrocarbons with no double bonds. In the present study, the reference molecules for ivyane numbers 2-4 have one or more double bonds and it is possible that the method does not work as well for that case. For [5]ivyane, the reference molecule is 3-methyl diadamantane and one expects the isomerization reaction to yield an accurate value of ΔfH°(g). The result for [5]ivyane (374.98 kJ/mol) is 10-15 kJ/mol higher than the results obtained from the bond separation and atomization reactions.

The data in Table 2 ΔfH°(g) computed from bond separation and atomization reactions agree extremely well with the experimentally derived values for gas phase alkanes with 4 to 20 carbon atoms (experimental data for larger hydrocarbons is not readily available). However, we observe a large systematic deviation between the computed and experimental values for the standard heat of combustion, ΔcH°(g) - the difference between experiment and calculation grows from 37.6 kJ/mol for C_{4}H_{10} to 174.0 kJ/mol for C_{20}H_{42}. The source of this discrepancy was traced to errors in the atomization energies for the reference molecules in the combustion reaction, namely O_{2} (-3.281 kJ/mol), CO_{2} (+4.807 kJ/mol) and H_{2}O (-1.060 kJ/mol). After adding these
corrections to the G3MP2//B3LYP energies of these species, the recomputed values of $\Delta H^\circ(g)$ are all within ±3 kJ/mol of the experimental values, as seen in Table 2. This correction makes the $\Delta H^\circ(g)$ values consistent with the $\Delta f H^\circ(g)$ computed using the atomization reaction.

Table 2. Gas phase enthalpies of combustion and formation for the normal alkanes from G3MP2//B3LYP calculations. Experimental data from NIST (reference 24). Values in italics are determined by extrapolation. Except as noted, all units are in kJ/mol.

<table>
<thead>
<tr>
<th>Alkane</th>
<th>$\Delta H^\circ$ exp</th>
<th>$\Delta H^\circ$ BS</th>
<th>$\Delta H^\circ$ ATO</th>
<th>$\Delta H^\circ$ exp</th>
<th>$\Delta H^\circ$ calc</th>
<th>$\Delta H^\circ$ corr.</th>
<th>$\Delta H^\circ$ kJ/g</th>
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<td>C4H10</td>
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Table 2 also contains values of the standard heat of combustion in units of kJ/g. This quantity varies much less with alkane size and is a useful quantity for extrapolating thermochemical properties for alkanes with up to C$_{32}$H$_{66}$, the average molecular composition of paraffin. $\Delta H^\circ(g)$ in kg/mol is estimated using the extrapolated kJ/g values and $\Delta f H^\circ(g)$ is computed from the heat of combustion. These values are also shown in Table 2 and Figure 11. They are then used to derive the extrapolated values of $\Delta f H^\circ(g)$ (Figure 9) and $\Delta H^\circ(g)$ (Figure 10) for the alkanes. Using the same extrapolation method, values of $\Delta f H^\circ(g)$ and $\Delta H^\circ(g)$ are estimated for [7]-[10]ivyanes (ivyanes with more than 8 cyclopropyl groups have not yet been synthesized). The extrapolated values are included in Figures 7 and 8. For [6]ivyanes $\Delta f H^\circ(g) = 440.4$ kJ/mol by direct calculation and for [7]- and [8]ivyanes $\Delta H^\circ(g) = 542.5$ kJ/mol and 647.6 kJ/mol by extrapolation, respectively.

For rocket propulsion applications the relevant heats of formation and combustion for fuel components must be for liquid or solid phase molecules. The calculated values
for normal alkanes and ivyanes are determined for gas phase species. In order to obtain the needed liquid and solid thermochemical data the heat of vaporization or sublimation must be available. For alkane chains up to 20 carbons in length $\Delta_{vap}H^0$ and $\Delta_{sub}H^0$ have been measured. For ivyanes, these quantities are not known. In Figure 12a experimental data for standard heats of vaporization and sublimation of normal alkanes are plotted versus the number of carbon atoms in the molecule. For vaporization, the curve is linear and extrapolation to larger molecules is easily carried out. For sublimation the data are more scattered and only an estimate of the heat of sublimation can be obtained. The extrapolations through $C_{32}H_{66}$ are shown in the figure. Our estimate for the standard heat of sublimation for paraffin is estimated to be $250 \pm 25$ kJ/mol, which when combined with $\Delta_fH^0(g)$ = -684.6 kJ/mol, from Table 2, yields a value of $-935 \pm 25$ kJ/mol which is in complete agreement with the value of $\Delta_fH^0(s)$ = -933 kJ/mol$^9$ cited in the Introduction. From Figure 12b, the estimated value of $\Delta_{vap}H^0$ for [6]ivyane is 75 kJ/mol and for [7]ivyane, the estimated value for $\Delta_{sub}H^0$ is 120 kJ/mol. This makes $\Delta_fH^0(l) = 365$ kJ/mol for [6]ivyane and $\Delta_fH^0(s) = 422$ kJ/mol for [7]ivyane. In reference 9 the results of a calorimetric study of [6]ivyane(l) are presented. That paper has a value of $\Delta_fH^0(l) = -12,300 \pm 600$ kJ/mol which is equivalent to $\Delta_fH^0(g)$ for cyclopropane. This relationship implies that the strain energy of [6]ivyane is greater than the sum of the cyclopropane strain energies, because [6]ivyane ($C_{18}H_{26}$) has 10 fewer hydrogen atoms than six cyclopropane molecules (each one $C_3H_6$) and five fewer $H_2O(l)$ are formed by the combustion reaction. The heat of formation of a single liquid phase water molecule is -285.83 kJ/mol, so the total contribution of these five water molecules to the heat of combustion energy is 1429.15 kJ/mol. Thus, there is a discrepancy in $\Delta_fH^0$ for [6]ivyane between the experimental value in reference 9 and the calculations presented in the present paper. However, even though the value we obtain for the standard heat of formation for [6]ivyane is considerably less than the value obtained from the colorimetric measurement$^9$, it is still quite high, indicative of the large strain energy in the cyclopropane rings.

We also carried out exploratory calculations to ascertain whether fairly simple chemical modifications of ivyanes could improve its performance as a rocket fuel additive. We selectively added methyl groups to the cyclopropyl rings to determine their effect on the thermochemical properties. Each added methyl group increases the overall H/C ratio slightly without significantly reducing the strain cyclopropyl energy. This approach was tried earlier in the Soviet Union with syntin, which is almost equivalent to [3]ivyane with an added methyl group. We also considered a new result from Sherburn and coworkers$^{25}$ who have prepared a modification of [3]dendralene with an allenyl group replacing the central C-C double bond. It is expected that the cyclopropanation reaction used to convert dendralenes to ivyanes will result in the formation of a spiropentyl group as shown in figure 13. Spiropentane ($C_5H_8$) is comprised of two perpendicular cyclopropyl rings with a common vertex, as shown in Figure 14. The central carbon atom is highly strained because it has two pairs of bonds with 60° angles.
Figure 13. Schematic drawing of (a) 1,1-divinylallene and (b) its cyclopropanation product.

Figure 14. Ball and stick model of spiropentane. The darker spheres represent carbon atoms and the lighter spheres are hydrogen atoms. The carbon-carbon and carbon-hydrogen bonds are indicated.

The results of these calculations are summarized in Table 3. The molecules are arranged with each parent ivyane. It can be seen that converting a cyclopropyl ring to a spiropentyl greatly increases the standard heat of formation. On the other hand, adding methyl groups to the cyclopropyl rings reduces it somewhat. However, the H/C ratio is increased by 0.1 to 0.2 with methylation and reduced by spiropentane formation, so the potential effect on $I_{sp}$ is unclear. Also in that table are heats of formation and combustion for the liquid rocket fuel syntin and cubane, a well-studied HEDM candidate, as well as hypothetical molecules tetrahedrane and ditetrahedryl. Cubane, a solid, and the tetrahedrane molecules, gases at room temperature, have extremely high values of $\Delta H^\circ$, but very low H/C ratios. So they are probably not good rocket fuel candidates.
Table 3. Thermochemistry of modified ivyanes and other HEDM candidate fuels as determined by G3MP2//B3LYP calculations

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<th>Molecule</th>
<th>$\Delta_h^o$ ATO kJ/mol</th>
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4. Evaluation of Ivyanes as Rocket Fuels

In order to predict the performance of new rocket fuels and fuel additives we assume thermochemical equilibrium is achieved at the combustor exit and throughout the nozzle. We use the CEA computer code\textsuperscript{26-28} (Chemical Equilibrium with Applications) that was developed by Gordon and McBride at NASA Glenn Research Center. CEA requires as input the mole fraction, stoichiometry and heat of formation of each fuel and oxidizer component as well as initial fuel temperature, mass of oxidize to mass of fuel ratio (O/F), pressure at the combustor exit and supersonic area ratio of the nozzle, and computes the exhaust gas temperature at the combustor exit, nozzle throat and exit, and $I_{sp}$ at the nozzle throat and exit. We considered both oxygen (O\textsubscript{2}) and nitrous oxide (N\textsubscript{2}O) as oxidizers. We determined $I_{sp}$ as a function of O/F for pure paraffin, pure [8]ivyane and a 1:1 blend (by weight) using O\textsubscript{2} and N\textsubscript{2}O as oxidizer. All calculations used a combustion chamber pressure of 500 psia and a nozzle area ratio of 300. The results are shown in Figure 15. It can be seen that [8]ivyane has a slightly higher $I_{sp}$ than paraffin and that the
peak I_sp is achieved at a lower O/F for both oxidizers. The values of peak I_sp are 383.7 at O/F = 2.5 for [8]ivyane versus 380.2 at O/F = 2.75 for paraffin with O_2 and 331.3 at 8.5 and 327.6 at 9.25, respectively, with N_2O. Results for modified [8]ivyanes with O_2 are shown in Figure 16a and similar results with N_2O are shown in Figure 17. At each value of O/F, the differences between ivyanes and paraffin are shown in Figure 16b. 

[8]ivyane+200 is approximately equivalent to spiro-ivyane. One can see that the difference in peak I_sp between [8]ivyane its methyl derivative is negligible, as the slight lowering of ΔH° is balanced by the slight increase in H/C. On the other hand, spiro-ivyane has a 2 s higher peak I_sp than ivyane. These results indicate that ivyanes and methylated ivyanes offer only a small advantage over paraffin as rocket fuel and negligible advantage as a fuel additive. It is possible that spiroivyane-paraffin blends could offer a slight advantage in performance over pure paraffin.

5. Conclusions

We have evaluated the potential benefit of using highly strained hydrocarbons such as the newly synthesized ivyanes as solid rocket fuels or fuel additives using a three pronged approach: experimental characterization of [6]- and [7]ivyane, calculation of their heats of formation and combustion using the G3MP2//B3LYP quantum chemistry method, and estimation of their I_sp using a chemical equilibrium model.

We have determined that [7]ivyane forms a stable 1:1 blend, but the melting temperature difference between paraffin and [7]ivyane is too large. [8]ivyane should have a melt temperature closer to that of paraffin. [6]ivyane does not form a good solid blend with paraffin because its melt temperature is well below 0 C, but it could be a good candidate for liquid fuel rocket applications. We could not determine vaporization energy or boiling points of these ivyanes, because they decomposed at temperatures above 200 C.

We have ascertained ivyanes have large positive heats of formation, due to the strain energy inherent in the cyclopropyl moieties. However, the calculated heat of formation for [6]ivyane is considerably less than the experimental value. The reason for this discrepancy is not known. We have validated our method for computing thermochemical properties with calculations of the heats of formation and combustion of normal alkanes. In addition, we have determined these thermochemical parameters for hypothetical methylated ivyane derivatives and molecules with cyclopropyl groups replaced by spiropentyls.

Our predictions of I_sp for ivyanes and modified ivyanes show only slight increase of the I_sp for paraffin. Thus it does not appear that ivyanes are suitable candidates to replace or augment paraffin as a fuel for hybrid rockets.

Acknowledgement

This work was supported in part by the NASA Ames Research Center Technology Innovation Fund.

References


26. CEA website: www.grc.nasa.gov/WWW/CEAWeb/ceahome.htm
Figure 4. DSC scans for [7]ivyane. (a) result using open sample container with the melt transition at 52.6 °C and oxidative decomposition for $T > 200$ °C. (b) and (c) result using closed sample container with $T_{mp} = 46.6$ °C and non-oxidative decomposition from 300 to 370 °C.
Figure 5. DSC scan for 1:1 paraffin:ivyane blend showing the melt transition at 49.2 C.

Figure 6. DSC scan for paraffin showing the melt transition at 66.8 C.

Figure 7. Enthalpy of combustion for gas-phase ivyanes calculated using the G3MP2//B3LYP method. The x-axis is the number of cyclopropane rings and the y-axis is the combustion enthalpy in kJ/mol. Dashed line values derived from extrapolation of $\Delta H^\circ$ in kJ/g.
Figure 8. Enthalpy of formation for gas-phase ivyanes calculated using the G3MP2//B3LYP method. The x-axis is the number of cyclopropane rings and the y-axis is the formation enthalpy in kJ/mol. Dashed line values derived from extrapolation of $\Delta_h^o$ in kJ/g.

Figure 9. Enthalpy of combustion for gas-phase alkanes calculated using the G3MP2//B3LYP method. The x-axis is the number of carbon atoms in the alkane and the y-axis is the combustion enthalpy in kJ/mol. NIST data are from reference 24.
Figure 10. Enthalpy of formation for gas-phase alkanes calculated using the G3MP2//B3LYP method. The x-axis is the number of carbon atoms in the alkane and the y-axis is the combustion enthalpy in kJ/mol. Dashed line values derived from extrapolation of $\Delta_{c}H^0$ in kJ/g.

Figure 11. Enthalpy of combustion for gas-phase alkanes calculated using the G3MP2//B3LYP method. The x-axis is the number of carbon atoms in the alkane and the y-axis is the combustion enthalpy in kJ/g. Dash line values are extrapolated as explained in the text.
Figure 12. Experimental Phase change enthalpies in kJ/mol for (a) normal alkanes and (b) other alkanes, including estimates for ivyanes from reference 24. Both vaporization and sublimation values are shown.
Figure 15. Dependence of $I_{sp}$ on oxidizer to fuel ratio for paraffin and [8]ivyane from CEA calculation for liquid oxygen and N$_2$O oxidizers.
Figure 16. Comparison of $I_{sp}$ for paraffin, [8]ivyane and chemically modified ivyanes using $O_2$ as oxidizer. (a) $I_{sp}$ and (b) $\Delta I_{sp}$ relative to paraffin. [8]ivyane-Me is methylated ivyane and [8]ivyane+200 is ivyane with $\Delta H^0$ increased by 200 kJ/mol to mimic spiro-ivyane.
Figure 17. Comparison of $I_sp$ for paraffin, [8]ivyane and chemically modified ivyanes using N$_2$O as oxidizer.