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To Infinity and Beyond: An Optimization Study of Kerosene and Hydrogen Peroxide Bipropellant Fuels

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ABSTRACT

Currently, hydrazine fuels are grossly inefficient in terms of environmentally friendliness and handling costs. Hydrogen peroxide (H_2O_2) and kerosene bipropellants have recently shown promise as a fuel that is similar in efficiency to hydrazine yet superior in cost and environmentally friendliness. Previous research on H_2O_2/kerosene bipropellants view environmentally friendliness, cost effectiveness, and fuel efficiency separately, making comparison between these properties difficult. This research uses calorimetry to provide a new method of quickly and precisely finding optimal ratios of fuels in bipropellants. For different ratios of fuel, efficiency was measured by finding the fuel mixture's specific energy, environmentally friendliness was measured by finding the fuel mixture's efficiency per carbon released into the atmosphere, and cost effectiveness was measured by finding the fuel mixture's efficiency per unit fuel cost. The Cobb-Douglas function was used to optimize for multiple fuel properties at the same time: environmentally friendliness and efficiency, cost effectiveness and efficiency, and environmentally friendliness and cost effectiveness. These double optimizations brought new properties of H_2O_2/kerosene bipropellant fuels to light, notably that the optimal ratio of fuel for environmentally friendliness coincides with the optimal ratio for fuel efficiency, and the bipropellant remains efficacious in terms of efficiency even while operating at the optimal quantity for cost effectiveness. In short, these findings reaffirm H_2O_2 and kerosene bipropellants as great potential candidates for an eco-friendly and cost-effective replacement of hydrazine because of their unique potential to remain environmentally friendly even at optimally efficient ratios.

Literature Review

With rapid developments in the space industry over the past decades, it is important to analyze the sustainability of the status quo. With an increased demand for satellites and research vessels in recent history, it is imperative that space travel technologies are improved to make the industry more efficient as it expands. A general spacecraft is composed of a payload, fuel tanks, and an engine. As chemical engines are by far the most effective at the time being, it is important to have an efficient chemical fuel to complement them (Kordina, 2020). Improvements in a fuel itself rather than in a rocket engine are necessary to add more total energy to the system and ultimately reach a higher maximum energy orbit.

Current rocket fuels are far from optimized. Hydrazine, the most commonly used fuel, is extremely toxic, combustible, volatile, and expensive to create. New candidate fuels include Hydroxylammonium Nitrate (HAN), a fuel that is "less toxic than caffeine," and hydrogen peroxide and kerosene hybrid fuels, which burn into water, oxygen, and nontoxic carbon compounds (Cervone et. al., 2006; Thompson, 2019). These fuels have been measured to have comparable efficiency to hydrazine, with HAN even being reported to have up to 50 percent more specific energy, or energy per unit of mass (Amrousse et al., 2017; Nguyen et al., 2020; Thompson, 2019; see also Moon et. al., 2014; Romantsova et al., 2015; Yun et al., 2021). In addition, hydrogen peroxide, kerosene, and HAN can be manufactured much more efficiently and safely than hydrazine as the chemicals are more stable without the erratic and unpredictable nitrogen bond found in hydrazine (Amrousse et al., 2017; Kleiner, 2008; Pelin et al., 2020). The stability of these new compounds is valuable in particular because of "the significant cost saving associated with the drastic simplification of the health and safety protection procedures necessary during propellant production, storage and handling," (Cervone et. al., 2006; see also Akhter & Hassan, 2021).

Furthermore, hydrazine is dangerous to both humans and the environment. In past hydrazine spills, cleanup has been monumentally difficult with largely irreversible damage to ecosystems (Kovshov, 2015). Additionally, being carcinogenic and toxic while also extremely volatile, transportation of hydrazine poses a risk to everyone involved and their surroundings (Douroudgari et al., 2021; Ingenito 2018). Even after being burned as fuel, hydrazine remains in the upper atmosphere for 32.8 to 1161.11 hours and in the lower atmosphere for 6.6 hours before degradation. Besides having an acute impact on the ecosystems around these affected areas, hydrazine does not break down into a safe, biodegradable molecule and instead remains in the atmosphere as a byproduct for extended periods of time (Douroudgari et al., 2021). The proposed alternative fuels do not have this problem; instead, they tend to break apart into simple molecules such as water, oxygen, and common polyatomic ions rather than long, stringy organic compounds that are unnatural in the Earth's atmosphere. Hydrogen peroxide fuels in particular are especially chemically simple, making them much easier to work with, less expensive to produce, and more promising as a potential future fuel (Cervone et al., 2006).

The scientific consensus agrees that green fuels are necessary to improve the space industry. Spaceflight in its current state is grossly inefficient and pollutes orders of magnitude higher than aviation on a per flight basis (Dodd et al., 2020; Kordina, 2021). Although there are not enough rocket launches to cause significant climate change in the modern era, as the industry advances along with technology, the demand for spacecraft and satellites are expected to increase dramatically. On top of this, rocket emissions affect the upper atmosphere much more than other types of pollution because of spacecraft reaching high altitudes, which has profound effects on the environment on a global scale (Kordina, 2021). The inefficiency of current fuel is bound to cause irreversible pollution if fuel standards remain the same in the near future (Dodd et al., 2020). The current debate is not over whether we should switch to environmentally friendly fuels, it is over our readiness to switch now and is over what the best new fuel would be (Manley, 2018). There is some debate on whether or not non-chemical based energy propellant would be more efficient in the future, but most agree that this is not feasible now (Kordina, 2021). Therefore, it is important to do research on the leading fuels to determine whether or not they can be used. Currently, hydrazine is the most available fuel and is the cheapest, so rocket manufacturers will continue to use it, but if more research is done on new alternative fuels, many agree that they could be cheaper than hydrazine once optimized (Manley, 2018).

Current research on alternative fuels tends to focus on one aspect of the fuel at a time rather than taking a holistic approach. For example, studies tend to either focus on the efficacy of these fuels in regards to either fuel efficiency or environmental friendliness, rather than both at the same time. Therefore, it is difficult to decide which fuels are most worthy to pursue scientifically due to the lack of knowledge of these fuels as a whole. This research will address this gap by asking the question: how can a kerosene and hydrogen peroxide bipropellant be optimized for energy efficiency, environmental friendliness, and cost effectiveness? The results of this research will serve to provide the space industry with useful information on fuel efficiency, environmental friendliness, and cost, so individual firms can better optimize their fuels for specific missions to not only allow for efficient spaceflight but also for cost-effective and environmentally-friendly spaceflight at the same time.

Additionally, more research on eco-friendly solid rocket boosters is necessary to curb dangerous lower atmosphere pollution in addition to research on eco-friendly liquid fuels (Cican & Mitrache, 2017; Yun et al., 2021; see also Murachman et al., 2013). Kerosene can be converted into paraffin wax and used as a more environmentally-friendly solid fuel, and although this research does not directly investigate paraffin wax, the results could have implications in this field as well due to the chemical similarities between solid paraffin wax and liquid kerosene (Akhter & Hassan, 2021).

The leading experts in hydrogen peroxide and kerosene bipropellant research are Cervone et. al., Li et. al., and Pelin et. al. Their research provides data on the manufacture and usage of hydrogen peroxide and kerosene bipropellants as an eco-friendly alternative to hydrazine. They have already conducted groundbreaking research on the efficacy of kerosene and hydrogen peroxide bipropellants and have paved the way for other researchers to further investigate and optimize the fuels.

I hypothesize that alternative fuels such as hydrogen peroxide-kerosene hybrid propellants can be optimized for environmentally friendliness and cost effectiveness while maintaining an efficacious fuel efficiency. I predict that combinations of fuel with higher amounts of peroxide will be more environmentally friendly as hydrogen peroxide does not emit carbon when decomposed, and I predict that these fuels will be better optimized for efficiency because the oxygen released by the hydrogen peroxide will allow more of the kerosene present to fully combust. I predict that cheaper fuels will contain more kerosene because kerosene is much cheaper to produce than hydrogen peroxide, especially at high concentrations.

Methods

A quasi experimental method was used to find the specific energy of different mixtures of paraffin oil (kerosene) and 32% hydrogen peroxide. This procedure is modeled after Grubelich and Melof's Investigation of Hypergolic Fuels with Hydrogen Peroxide (2000). Their procedure consists of lighting various mixtures of hydrogen peroxide with different fuels and catalysts to measure which ones will have the most violent reactions and which ones will ignite the fastest. Instead of doing a drop test, this procedure uses calorimetry to replace the qualitative measurement scale of 0-2 for reaction violence and reaction delay with a quantitative measurement of energy released. The calorimeter is used to get a quantitative measurement on the energy released in lieu of the qualitative scale for reaction violence, and the length of wick burned is measured in lieu of the qualitative scale on reaction rate (i.e. if more of the wick burns then there is a faster reaction rate in a fixed amount of time). Because this procedure measures one fuel combination specifically rather than comparing many different fuel quantities, a quantitative scale is justified so the data can have real world backing rather than being limited to comparison within the framework of other fuels.

To measure the amount of energy released by the burning of each fuel, a calorimeter setup was used. The calorimeter is composed of an insulated beaker which is placed on top of a metal stand. The beaker is lined with aluminum foil on the sides and top to prevent the loss of heat in the beaker to the environment, but the bottom of the beaker was left uninsulated to allow heat to transfer in from the bottom. A thermometer that does not touch the sides of the cup is secured by a clamp to stay in one place. The aluminum compartment is filled with 100mL distilled water, and a metal canister is placed under the cup with the desired quantity of fuel within. A fiberglass wick is left to soak completely in the fuel. The length and weight of the wick are measured before submersion in the fuel and after complete saturation. The volume of fuel in the canister is measured before and after submersion as well. When assembled with the fuel canister below the insulated beaker compartment, the wick is lit as quickly as possible to ensure that as little external energy enters the system as possible and the starting temperature of the water is recorded. The water is periodically stirred using a stirrer, a thin aluminum rod with a large ring on the end. The ring is placed inside the water through a small hole made in the top layer of aluminum foil and can be used to externally stir the water so that the heat is evenly distributed around the water, ensuring accurate measurements. After two minutes, the final temperature of the water is recorded and the flame is extinguished. The new length of the wick is measured and the wet wick is weighed after the fuel is burned. All of the collected data can be used to calculate the specific energy of different fuel mixtures, specifically the amount of fuel burned can be calculated from the change in fuel volume, the change in mass can be calculated from the change in the mass of the wick, and the change in energy can be derived from the change in temperature from the water. The procedure was iterated for eight combinations of 100mL of fuel, changing the combination by 5mL each iteration. For example, 100mL kerosene mixed with 0mL H_2O_2 was used, then 95mL kerosene mixed with 5mL H_2O_2 was used, and this pattern repeated until 65mL kerosene and 35ml of H_2O_2 were used. Any combinations with lower percentages of kerosene present were too difficult to light consistently and would burn so weakly that they were unable to be measured and were deemed nonoptimal. The wicks only soaked up a fraction of the fuel that they were submerged in, so a second trial was conducted after the first reusing the same fuel. Because the fuel is chemically the same between trials, this was done to gain data with different ratios of fuel than previous trials covered, since the wicks did not saturate evenly. New wicks were added and were allowed to soak overnight, adding different ratios of kerosene to peroxide to the data set.

The purely analytical method of calorimetry makes it easy to control for outside variables, but there were some variables that needed special attention. Because a 32% hydrogen peroxide solution was used in lieu of a highly explosive 95% or higher solution of hydrogen peroxide, there was some water present in the mixture of hydrogen peroxide and kerosene. To ensure that this water had no significant effect on the outcome of the experiment, a 100 percent water canister was measured as a control, along with an empty canister to measure the energy contained in the wick itself.

This specific methodology was chosen to find a relationship between the percent of kerosene in a kerosene and peroxide solution and the specific energy of said solution. The specific energy is important to find because the more energy per unit mass that a fuel has, the cheaper it is to transport to higher altitudes and the more efficient one unit of the fuel is at accelerating a spacecraft.

The resulting data was then analyzed using optimization methods. The equation to be maximized was chosen to be $f(x) = x$ for one variable and $f(x, y) = x^{.5} + y^{.5}$ for two variables. For one variable, maximizing is as simple as finding the highest measured value of the quantity, so finding the highest single value of x (representing the value of measured quantity) would sufficiently maximize this value. A multitude of equations can be used to maximize for two variables, but $f(x, y) = x^{.5} + y^{.5}$ was chosen for its simplicity, practicality, and generality. Because the variables are both weighted by their square roots, increasing higher values of single variables contributes less and less additional value to the overall total, so it is much more likely that the resulting fuel will have some of both qualities, which is the goal of the optimization. The equation can be easily adjusted to add more variables, simply by adding another variable into the equation with the same power (i.e., $f(x, y, z) = x^{.5} + y^{.5} + z^{.5}$). Although this research will not investigate any triple-optimizations, it is entirely possible and applicable for other research to do this with the same method. These equations are modeled after the Cobb-Douglas production function, a common optimization formula in multivariable mathematics, and the exponent weights on each of the variables can be changed to fit any specification if one of the variables matters more than other for a specific fuel.

The single quantities that were investigated were fuel efficiency, environmental friendliness, cost efficiency, and the pairs of quantities that were optimized for were cost efficiency and environmental friendliness, cost efficiency and fuel efficiency, and environmental friendliness and fuel efficiency. Although all of these variables matter a great deal in a fuel, their values differ in orders of magnitude. To compare them properly, they were converted to numbers between zero and one, with the lowest value of a variable being assigned zero and the highest value of a variable being assigned one. The rest of the values between the maximum and minimum will be adjusted to some number between zero and one based on a linear scale. This eliminates the bias towards higher order of magnitude measurements in the optimization calculation.

Results

After the sample data was collected (see Table 3 and 5 in Appendix A), it was analyzed to find the amount of each substance burned, the ratio between these substances, the amount of energy released, and the specific energy of the compound (see Table 4 and 6 in Appendix A). The volume of kerosene and H_2O_2 solution that burned was calculated by taking the percentage of wick that was burned ($\frac{Change\ in\ Wick\ Length}{Original\ Wick\ Length}$) and multiplying it by the change in volume of kerosene and H_2O_2 solution, respectively. The energy released was calculated by multiplying the change in water temperature with the mass of water (.1kg) and the specific heat of water (4.184kJ/kg°C). The specific energy was calculated by dividing the change in energy by the amount of mass burned of the solution. The mass of the solution was found by taking the change in mass of the wick from wet to dry, multiplying it by the percent of the wick that was burned, and subtracting out the .68g of water per mL of 32% H_2O_2 solution. Because the experiment was conducted outside at the request of the IRB to increase safety in the event of a fire, the data is separated into two separate groups to account for the different weather on the two days that data was collected. The two separate data sets can be analyzed separately, but because it is impossible to control the exact conditions that each data set was tested in, comparing the two to each other directly should be done in caution.

It seems that the kerosene and hydrogen peroxide generally saturated the wick at a ratio of around 70% kerosene to 30% hydrogen peroxide, even when soaked in mixtures of different ratios, simply because the chemicals became balanced in the wick at this ratio. Fortunately, the data in this area is rich and carries a lot of information. As seen in the Graph 1 and Graph 2, the data forms a trend around which peaks at 65 to 70 percent kerosene, slowly tapering off as more kerosene is added and quickly tapering off as more peroxide is added. There was one outlier at 56 percent kerosene. This was the lowest percentage of kerosene tested, since all other attempts to test lower kerosene ratios than this resulted in failure because the high quantities of water present in the hydrogen peroxide solution act as a flame retardant. This outlier cannot be ignored, and could be an important piece of data when investigated further, but it is wildly off of the trend of all of the other data, so a separate graph is included with the outlier removed to more easily see the trend of the other data. The outlier can be explained since such a high concentration of hydrogen peroxide and water was used, some of the water may have evaporated due to the high volume, causing a higher concentration of peroxide than measured to be saturated into the wick. In previous tests, it was difficult to even light anything lower than 65 percent hydrogen peroxide, further affirming that less water than initially believed may have been present in the wick.

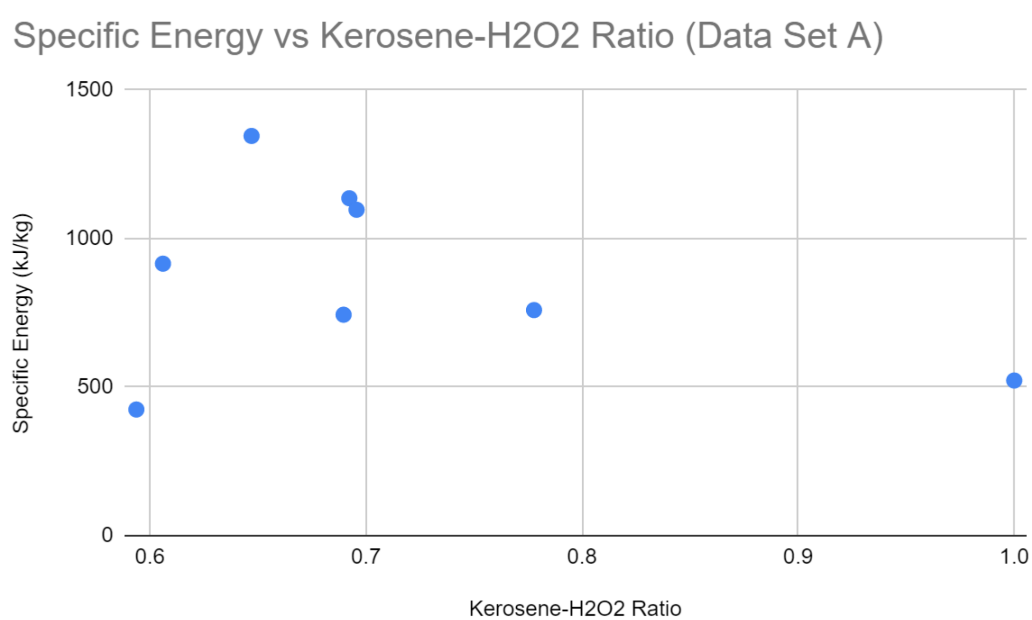

Figure 1. Specific Energy vs Kerosene- H_2O_2 Ratio (Data Set A)

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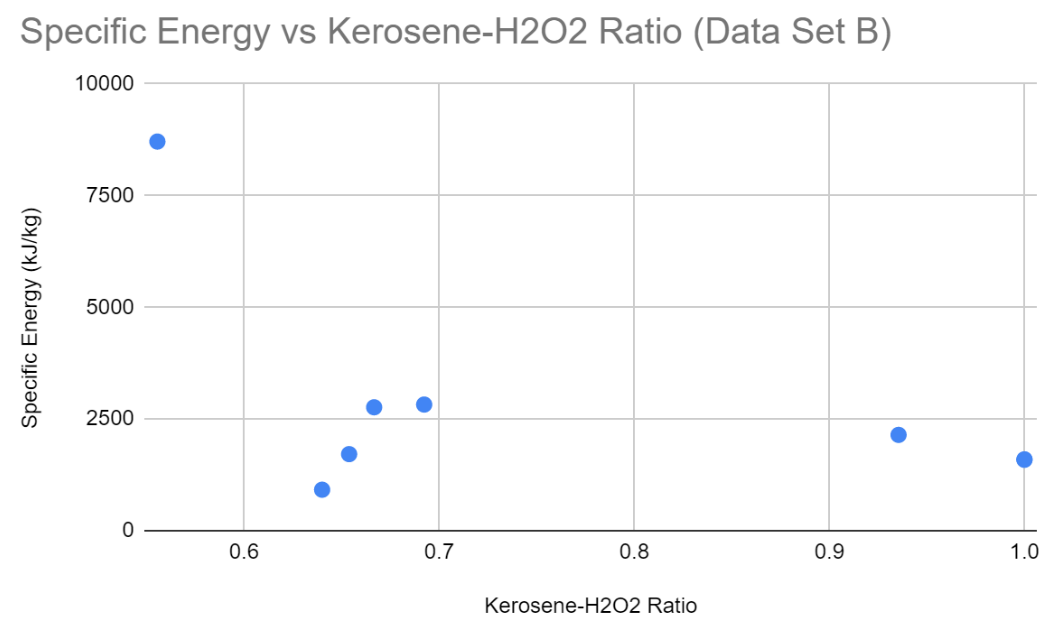

Figure 2. Specific Energy vs Kerosene- H_2O_2 Ratio (Data Set B)

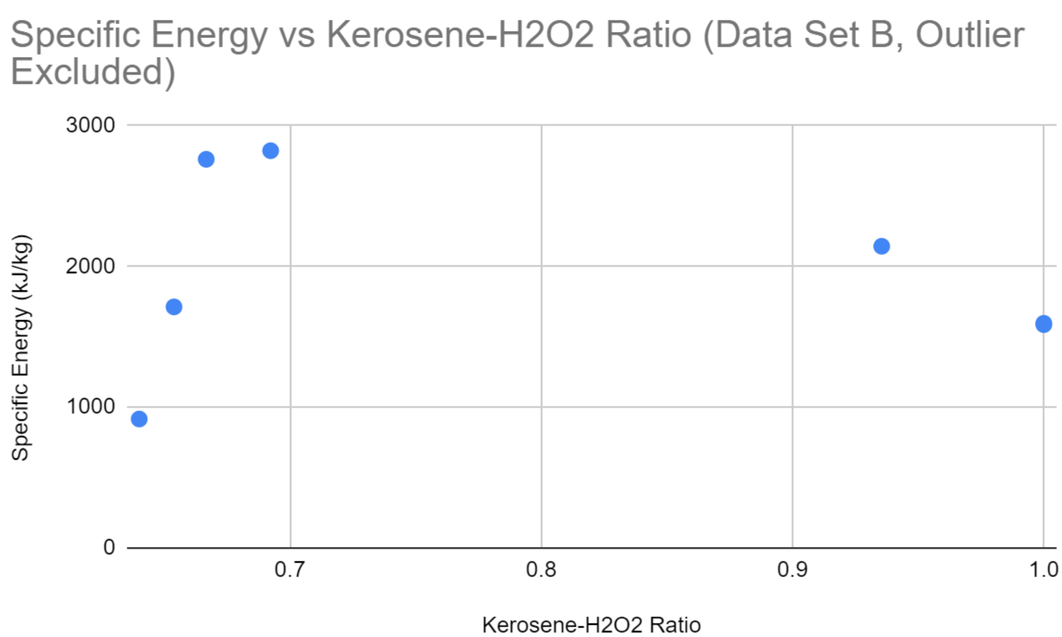

Figure 3. Specific Energy vs Kerosene- H_2O_2 Ratio (Data Set B, Outlier Excluded)

The trends in this data make sense with the hypothesis because there is a sharp decline to the left of the optimal point and a slow decline to the right of the optimal point. This is because hydrogen peroxide by itself is not flammable and will quickly put out a flame if present in too high of a ratio. Having too much kerosene will still result in a flame, but if not enough hydrogen peroxide is present it will slowly become less efficient because of the lack of oxidation. In data set A, the maximum value of specific energy is achieved at 65 percent kerosene, where in data set B, the maximum value (excluding the outlier) is achieved at 69 percent kerosene.

The trend continues in the aggregate data (seen in Graphs 4 and 5 below), although slightly less apparent. Because the values of the energy data in Data Set B tended to be a little higher due to different testing conditions, few conclusions can be drawn from the aggregate data specifically, and each individual trial of data should be viewed as a standalone and compared to each other in trends to draw more scientifically sound conclusions.

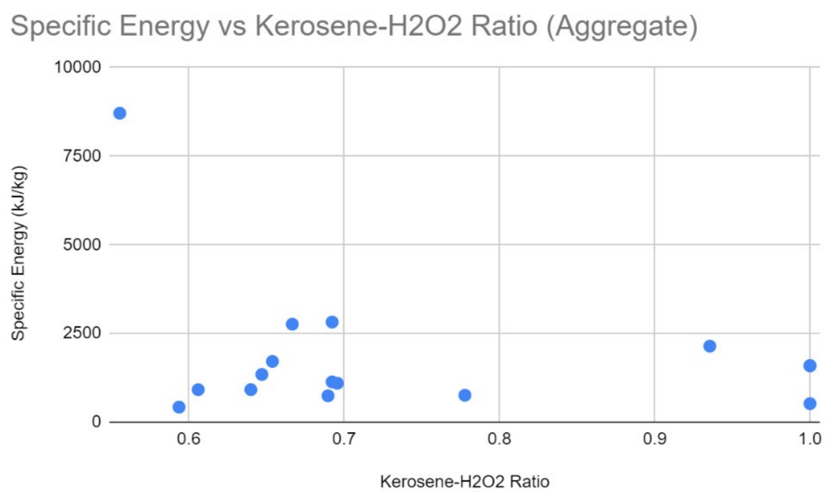

Figure 4. Specific Energy vs Kerosene-H_2O_2 Ratio (Aggregate)

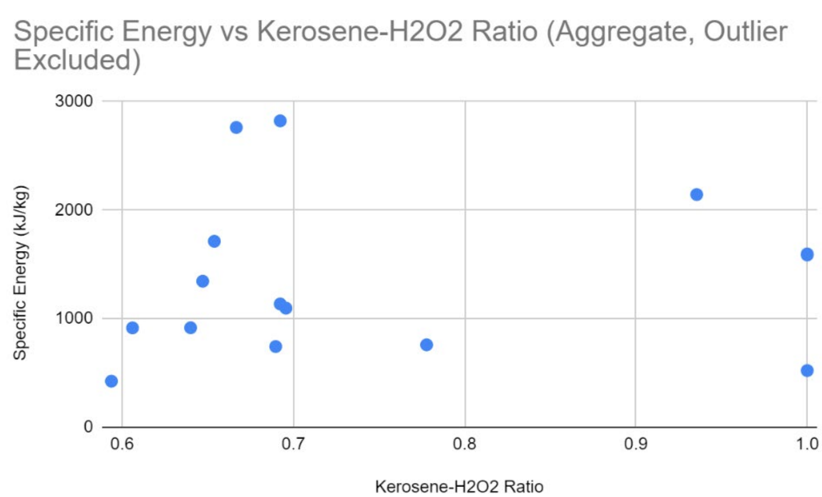

Figure 5. Specific Energy vs Kerosene-H_2O_2 Ratio (Aggregate, Outlier Excluded)

Although the aggregate data is flawed in that values from data set B tend to be higher than values in data set A because of the inability to control for weather, it is definitely apparent that the data peaks around 67% kerosene then tapers off as it approaches 100% kerosene.

During the experiment, it was qualitatively observed that kerosene tended to burn more quickly than hydrogen peroxide, usually consuming most of the wick by the time the trial ended in two minutes. Although slower and with a less vibrant flame, the hydrogen peroxide mixtures tended to burn stronger but slower, allowing for an efficient flame that released energy in sustained bursts. As more hydrogen peroxide was added, the mixture became more and more difficult to light, but once lit was able to remain lit for longer with a slow burning flame.

Discussion

Overall, the newly constructed method was very successful at finding the optimal ratio of kerosene and hydrogen peroxide to be between 65 and 70 percent kerosene to peroxide. More exactly, the maximum specific energy value for each data set was found at 65 and 69 percent kerosene, respectively, and averaging these values yields a calculated optimal quantity of 67 percent kerosene by volume for specific energy. This combination provides the highest amount of energy per mass and is the most efficient ratio of hydrogen peroxide to kerosene in terms of fuel economy. However, the method also allows for the optimization of hydrogen peroxide and kerosene mixtures for other measurable quantities, such as eco-friendliness and cost-effectiveness. The eco-friendliness of a mixture can be modeled as the specific energy per percentage kerosene. Kerosene is more eco-friendly than current rocket fuels such as hydrazine, but still produces carbon dioxide which could be harmful to the atmosphere in large amounts. On the other hand, hydrogen peroxide does not produce any harmful compounds (decomposing into oxygen and water). However, hydrogen peroxide by itself is not flammable, so just saying that a 100 percent hydrogen peroxide fuel is the most eco-friendly would not work, and using a 20 percent kerosene fuel to tout "environmentally friendliness" would be so inefficient that it would end up burning so much more fuel than normally required to get out of the atmosphere that it would cancel out all of the positive environmental effects. Therefore, an analysis of "efficiency per carbon released into the atmosphere," or specific energy per percent kerosene, is used to determine environmental friendliness. A similar logic is used to explain the cost-efficiency. Since putting more mass into space is expensive, one cannot simply assume that a 100 percent kerosene fuel would minimize cost, as the reduced efficiency could require more fuel to actually reach the atmosphere, costing more overall. Maximizing an "efficiency per cost," or specific energy over total cost (total cost equals the price of kerosene times the volume of kerosene plus the price of hydrogen peroxide times the volume of hydrogen peroxide), was used. The analyzed data were indexed and are included in Table 1 and 2 on the next page.

In both cases, excluding data point 13 as an outlier, the maximized cost value is at 100 percent kerosene, and the value decreases until around the optimal quantity of fuel for efficiency, where there is a small spike up in cost efficiency before a rapid decline. The eco-friendliness of a fuel is maximized at around 65 to 69 percent kerosene, with an average of 67 percent kerosene, the same as the optimal quantity for fuel efficiency. These results are reasonable because kerosene is much cheaper than hydrogen peroxide while only having slightly less efficiency. Although a 100 percent kerosene rocket would need more fuel to function due to the loss of efficiency, the sharp decline in price more than makes up for it in terms of cost efficiency. On the other hand, the optimal value for environmental friendliness being the same as the optimal value for energy efficiency makes sense, as having higher quantities of hydrogen peroxide quickly diminishes the energy efficiency to a degree that does not justify the increased environmental returns.

Table 1. Eco Index Values for Samples **Table 2. Affordability Index Values for Samples**

Eco Index Data Set A	Eco Index Data Set B	Sample (Set A, Set B)	Affordability Index Data Set A	Affordability Index Data Set B
191	514	1,9	458002	1400421
372	641	2,10	122940	1391925
767	1281	3,11	147219	823884
673	4077	4,12	90979	317667
466	20759	5,13	139981	776915
606	2305	6,14	136482	347934
308	1623	7,15	90926	190680
158	692	8,16	41033	98559

To optimize for multiple factors at once, a double optimization technique with the equation $f(x,y) = x^{.5} + y^{.5}$ was used, with x and y representing the input values of the parameters to be maximized and $f(x,y)$ representing the equation to be maximized. To make the indices comparable, the magnitude was adjusted to be between zero and one by changing every value to a percentage of the maximum. This allows each index to carry the same weight in the equation. Using a Python script (see Appendix C), each value was procedurally entered into the equation and the percentage of kerosene yielding the maximum value of $f(x,y)$ was recorded. It was determined that the optimal percentage of kerosene for a cost effective and eco-friendly fuel was 82.5%, the optimal percentage of kerosene for a cost-effective and energy efficient fuel was 100%, and the optimal percentage for an eco-friendly and fuel efficient fuel was 66% kerosene.

Conclusion

In conclusion, calorimetry can be a viable method to optimize bipropellant rocket fuels. This was done specifically for a hydrogen peroxide and kerosene bipropellant, with the optimal ratio being found to be 67% kerosene and 33% hydrogen peroxide. There was an intriguing outlier at 56% kerosene and 44% hydrogen peroxide with an uncharacteristically high specific energy that future researchers could investigate further, although higher concentration hydrogen peroxide or a bomb calorimeter may be required to consistently ignite mixtures with lower concentrations of kerosene. The calorimetry method devised in this research is advantageous to other previous methods of fuel optimization in that a best fit trendline can easily be set to the data and can be used to optimize for more than just fuel efficiency. Past research has only attempted to optimize for fuel efficiency, but the equations derived from the calorimetry data in this experiment were used to optimize for fuel efficiency and cost at the same time and fuel efficiency and environmentally friendliness at the same time using a Cobb-Douglassian model. The double-optimizations were found to have an optimized quantity at 82.5% kerosene for cost and environmentally friendliness, 100% kerosene for cost and fuel efficiency, and 66% kerosene for fuel efficiency and environmentally friendliness.

Despite the method's practicality at optimizing fuel efficiency for multiple applications at once, it is important to understand that the calorimetry data, although precise, does struggle at producing results accurately. Essentially, the calorimetry method can be used to find the optimal ratio of two fuels, but cannot determine exactly how efficient the mixture will be. It is impossible to perfectly trap heat, no matter how high quality of a calorimeter one uses, so measurements will never be perfectly accurate. Using the same calorimeter for multiple measurements can allow for very precise comparisons between those measurements, but the values will not be exactly the same in practice.

The results from this experiment further affirm the potential usefulness of a hydrogen peroxide and kerosene bipropellant as a safe, eco-friendly, and efficient form of fuel. Because the optimal quantity for fuel efficiency and eco friendliness together is so close to the optimal quantity for fuel efficiency (66% instead of 67%), the usage of the fuel in its most environmentally efficient form should not pose any problems for prospective space firms needing an energy efficient craft. For those that are looking for a cost effective fuel, closer to 100% kerosene may be a better option, and 82.5% kerosene can be used if extra energy is needed in conjunction with a low cost. Although pure kerosene propellants do not experience the same environmental benefits as kerosene and peroxide bipropellants, they are still much more environmentally friendly than hydrazine since they only leave carbon in the atmosphere rather than toxic organic compounds that cannot be broken down naturally. From the results of this research, the future of the space industry is promising, as it was determined that environmentally friendly and cost effective fuels can remain efficacious in terms of efficiency. In the future, similar research can be done on other prospective fuels such as HAN to optimize them for similar factors, or hydrazine could even be optimized in a similar manner to help curb the negative environmental impacts of the fuel.

Limitations

Because of the constraints of the lab in which the experiment was conducted, there were some imperfections in the results. For one, fuels will normally be burning in a 100 percent oxygen atmosphere, with liquid oxygen being supplied by an oxidizer tank on the spacecraft. In the future, this study could be replicated in a controlled environment with 100 percent oxygen rather than at standard atmospheric temperature and pressure. Further, since oxygen is a byproduct of the decomposition of hydrogen peroxide, the inclusion of higher concentrations of hydrogen peroxide can cut down on the amount of oxidizer necessary to burn fuel, decreasing the mass of a spacecraft and allowing it to reach higher energy orbits. Future research could address this concern by burning different concentrations of fuel and oxidizer in model rocket engines in a similar method, measuring total impulse (change in momentum) on the spacecraft rather than total energy. This procedure could yield more accurate results if a bomb calorimeter is used instead of a coffee cup calorimeter. The equipment is specialized and expensive, and was not available in any nearby labs to use. The experiment also needed to be conducted outdoors due to the lack of a suitable fume hood and the possible volatility of the hydrogen peroxide and kerosene mixture that the lab was not able to handle indoors. Because 100 percent hydrogen peroxide is an extremely volatile oxidizer, it is somewhat dangerous to work with and difficult to come by. Therefore, lab grade 32 percent hydrogen peroxide was used instead. The water used to dilute the hydrogen peroxide may have slowed the reaction and made the mixture harder to light, but the water was factored out of the mass of the fuel and should not have changed the specific energy at all (although it may have had an effect on the specific power because it could have changed the burn rate). The experiment was controlled as much as possible so that even if there is an inaccuracy in the data itself the measurements will be precise enough to compare to each other and optimize fuels on a relative scale that can compare to a global scale. In some experiments, a catalyst is used to speed up the hydrogen peroxide reactions, which was not done in this research. Perhaps a future experiment could test a catalyst with this procedure to find if it would increase the power of the efficient hydrogen peroxide concentrations.

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