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The Case for Solar Thermal Steam Propulsion System for Interplanetary Travel: Enabling Simplified ISRU Utilizing NEOs and Small Bodies

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Abstract

Sustainable space exploration will require the use of off-world resources for propellant generation. Use of off-world-generated propellant will significantly increase the range and payload capacity of future missions. Near-Earth Objects (NEOs) contain a range of available resources, including water as ices and hydrated minerals. However, water-bearing regolith would need to be excavated and the water extracted. Water is a compelling choice for fuel as it can be electrolyzed using solar photovoltaics to produce hydrogen and oxygen that is combusted to provide thrust. Our earlier work shows Isp of 350 to 420 s can be achieved. However, this water contains impurities including carbon monoxide and sulfur that can shorten the life of high-efficiency electrolyzers. Complex processes are required to remove these impurities, which makes water extraction from NEOs challenging by electrolysis. A credible alternative is to simply extract water, together with impurities, and heat it into steam for propulsion. Early techniques have proposed nuclear reactors for generating heat. In this paper, we propose using solar concentrators and carbon-black or Vanta-black™ nanoparticles to heat the water into steam. This solar thermal heating (STH) process converts 80 to 99 % of the incoming sunlight into heat. The process is efficient and contains no moving parts. Heat is first used to extract water, which is then condensed as liquid. Steam is then formed using solar thermal reflectors that concentrate the Sun's heat onto a nanoparticle covered surface. In theory, the water can be heated to 1000 ^{o}K to 3000 ^{o}K with Isp of 190 s to 320 s. This approach, while not offering superior propulsion performance compared to hydrogen-oxygen combustion, is simple and robust. Steam-based propulsion is comparable to current monopropellants or even some bi-propellants used on upper stages of interplanetary spacecrafts. This propulsion system can offer higher thrust than current electrical propulsion: there is also minimal risk as the water is inert and easily stored. Preliminary laboratory experiments support our theoretical results.

Keywords: Small Spacecraft, ISRU, Steam, Propulsion, System Design

1. Introduction

Miniaturization and improved performance of electronics, power systems, guidance, navigation and control devices on space systems have led to ever smaller, but capable spacecraft. These technological improvements have translated into reduced mass and volume, resulting in significant launch cost savings. Thus, small spacecraft are becoming popular platforms for interplanetary exploration and travel. Small spacecrafts, however, face important challenges with propulsion that limit their current applications. State-of-the-art electrical propulsion technologies demonstrated on large spacecraft do not readily translate to small spacecraft. The principal limiting factor for small spacecraft is the reduced power available and thus low-thrust. This is a major challenge when a small spacecraft needs to get into a capture orbit around another body or achieve escape velocities. Low-thrust solutions require long wait times and careful maneuvering, which is a major deficiency for small spacecraft missions. A better solution is needed. In this paper, we present solar thermal propulsion aided using carbon nanoparticles for small spacecrafts (Figure 1) and CubeSats.

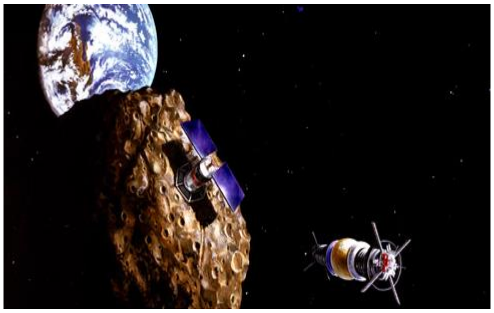

Fig. 1. Water extracted from asteroids and small bodies can be readily used as fuel in a solar thermal steam propulsion system (courtesy NASA).

Thermal propulsion technologies have been already proposed and many require a nuclear reactor to heat water into steam for propulsion. In our approach, we intend to use solar concentrators that utilize carbon nanoparticles to maximize solar to thermal energy conversion and heat water [18]. Using standard carbon nanoparticles, 80 % conversion efficiencies can be achieved. Using Vanta-black™, these efficiencies jump to 99 %. A deployable parabolic solar concentrator would be used [2, 4]. Solar energy is concentrated and converted to heat that is used to convert liquid water into high temperature steam. Temperatures of 1000 ^{o}K to 3,000 ^{o}K can be achieved with suitable concentrators and heat transfer systems. This translates into Isp of 190 to 320 s.

Our solar thermal steam propulsion system has four important characteristics. Firstly, the propellant is safe, easy to store, low-cost and minimizes launch risks from accidental combustion. Secondly, the propellant could in theory be generated using In-situ Resource Utilization (ISRU) on asteroids or comets. The water does not have to be purified or distilled as with electrolysis. Thirdly, the technology utilizes energy from the Sun much like electric propulsion, but with much higher conversion efficiencies. The proposed system is not limited to photovoltaics that have conversion efficiencies of only 29 to 35 %. Fourthly, the proposed system can produce high thrust, which is critical for getting into capture orbit or for making escape maneuvers as opposed to ion- or electrospray- based electric propulsion systems.

The elegance of the proposed method is that it is relatively simple and approaches the performance of bi-propellant propulsion, but without the challenges of propellant storage and safety. It is the system-wide simplicity of this proposed approach that makes the method tractable for ISRU. In due course, with further refinement to water capture and processing on small bodies, other higher performance techniques such as water electrolysis could be bootstrapped to this method. In the following sections, we present background and related work on solar thermal propulsion (Section 2), description of the solar thermal propulsion (Section 3), analysis and discussion (Section 4), feasibility experiments (Section 5), discussion (Section 6) followed by conclusions and future work (Section 7).

2. Background and Related Work

C-class asteroids are spectroscopically similar to carbonaceous chondrites; some are thought to contain significant amounts of water. Some meteorites, such as the Orgueil (CI) carbonaceous chondrite, contain about 20 wt % water: by extension, asteroids of similar composition may have water content up to 5-20%. However, in addition to water, heated meteorites, such as Orgueil, also release a range of other gases including SO_2, CO, and CO_2. Thus, any extracted water may contain impurities harmful to water electrolysers that would generate hydrogen and oxygen. However, water heated to high temperatures can act as a propellant in the form of superheated steam. If heated above 2000 ^{0}C water begins to split into hydrogen and oxygen. though this process is inefficient until T > 3000 °C. Hydrogen alone can be used as a propellant, which because of its low molecular mass can achieve high Isp.

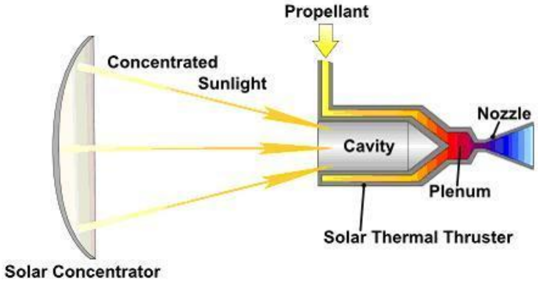

Fig. 2. Schematic of solar thermal propulsion. (Image courtesy Laboratory of Space Systems, Hoikado University, Japan).

The water can be heated using solar energy to achieve propulsion of the spacecraft. Solar thermal propulsion (STP) can be achieved in two ways: direct and indirect.

Direct Solar thermal propulsion involves heating the propellant directly using solar concentrators while indirect solar thermal propulsion uses heat exchangers or a thermal storage system to heat the propellant. Nakamura et al. [5] proposed use of fiber optics to transfer the light from the concentrator to the solar-thermal convertor. Alexander et al. [7] characterized a rocket that heated hydrogen using solar energy, providing 10 kW of power. They found combustion chamber temperatures of 2333 K and temperatures can be raised to 2866 K by optimizing the fuel flow rate. Direct solar collection combined with a re-radiator wall was developed to capture secondary radiation from the working fluid [8]. Heat exchangers can complicate system design while also increasing mass of the entire satellite.

Thermal storage materials have been proposed for energy collection and storage. Boron was proposed and tested by Schafer [9], achieving local temperatures ≥2570 K using a spherical concentrator and a Heliostat. This system was a hybrid system designed to provide both power and propulsion to the spacecraft.

Selective absorptive coatings are attractive due to the inherent simplicity of design. Cavity absorbers have been studied and rhenium was proposed as an attractive material given its high absorptivity, stability with hydrogen and high melting point of 3500 K [10]. However, rhenium is one of the rarest metals and one of the heaviest with atomic number 75. Spectral selective absorbers have been developed for applications on earth. A combination of nickel-nano-pyramids and an aluminum oxide coating has achieved maximum absorbance near the 1 micron spectrum [11]. For higher temperatures, transparent conductive oxide thin films on a metal substrate have been developed with emissivity of 0.11 and absorptivity of 0.71 [12]. Selective absorber materials haven't been developed for very high temperature applications. This is partly because there are few materials that have melting points above 2500 ^{o}K while having the necessary optical properties.

3. **Solar Thermal Propulsion**

In this paper, we propose the development of a solar thermal steam propulsion system for small spacecrafts and CubeSats. Solar energy is concentrated using a parabolic solar thermal concentrator onto a surface coated with carbon nanoparticles (Fig. 3, 4). The carbon nanoparticles have high light absorptivity of 80 % to 99 % and convert the sunlight into heat. The heat is then transferred to the water. The water is heated into steam [18] that is directed outwards into a jet using a specially designed bell nozzle.

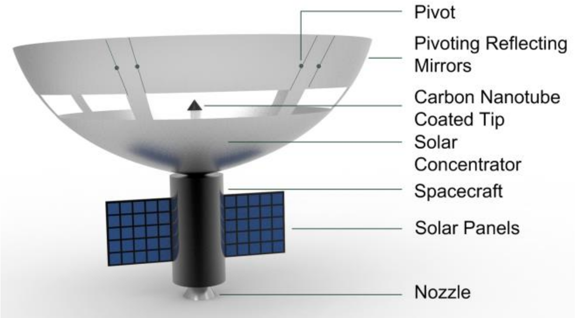

Fig. 3. Solar Thermal Propulsion System Concept

The parabolic concentrator will contain movable reflective mirrors attached to its periphery. The reflective mirrors will be used to reflect sunlight into the concentrator when the spacecraft is heading away from the sun. Using the movable reflective mirrors, the spacecraft can travel in any direction.

For our spacecraft concept, we consider a mission from Low Earth Orbit (LEO) to the Martian moon Phobos and back. The escape velocity for Phobos is 12 m/s and the delta-v of 3.5 km/s would be sufficient to reach Earth LEO on this return trip [13].

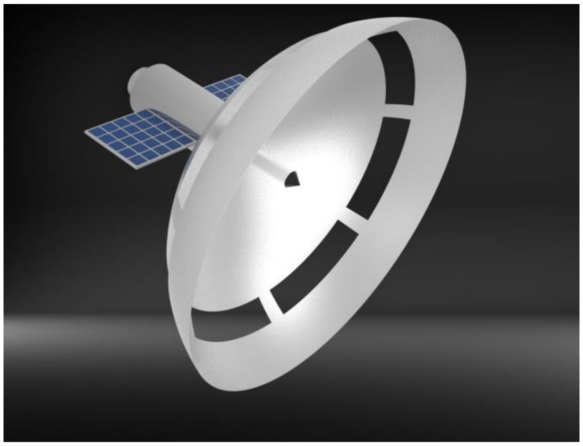

Fig. 4. Solar thermal propulsion system concept.

Water would be extracted from Phobos regolith by first collecting the regolith into a storage tank and heating it to release water. The proposed solar thermal propulsion is applicable in the inner solar system. Beyond Mars, the solar insolation drop-off makes the approach infeasible. For a trip to Phobos, solar irradiance at earth is 1365 W/m^2 while near Mars it is 590 W/m^2 [14-15]. This insolation decrease increases the proposed parabolic dish size and the accuracy requirement for the focal point.

Direct solar collection ensures the heat is focused directly onto the working fluid rather than on a heat exchanger, decreasing the heat losses (see Fig. 5). Heat exchangers can complicate system design while also increasing mass of the entire spacecraft. A parabolic dish (point heating) is preferred to a parabolic trough (linear heating) to achieve high concentration ratios.

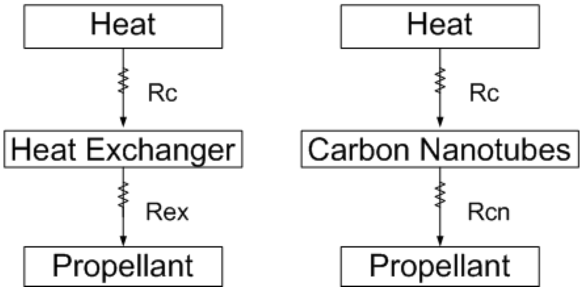

Fig. 5. Simplified resistance model comparison. Rex> Rcn implies higher heat loss for a heat exchanger.

The degree of light absorptivity of the receiver material is a crucial parameter. Conventional black paints have absorptivity ~0.95. The inherent problem with them is that they turn gray due to prolonged radiation exposure in space and hence reduce their absorptivity. Carbon nanotubes have an absorptivity of 0.99. They have been grown on Inconel 600 which is the preferred material for high temperature steam generation applications [16]. This can increase the efficiency of heat collection.

Inconel melts between 1350-1413^{0}C which is below the requirement of 3000 ^{0}C. Therefore, metals such as tungsten which melts at 3500 ^{0}C are required. In addition, carbon nanotubes have been grown on tungsten using chemical vapor deposition (CVD) [17]. Recently Surrey Nanosystems developed Vanta-black™ consisting of carbon nanotubes covered surfaces. These covered surfaces have an absorption of 99.9% at 750 nm spectral wavelength and comparable performance across the entire solar spectrum (Fig. 6). Vanta-black™ has space heritage having been recently used as a coating on the Kent Ridge 1 satellite.

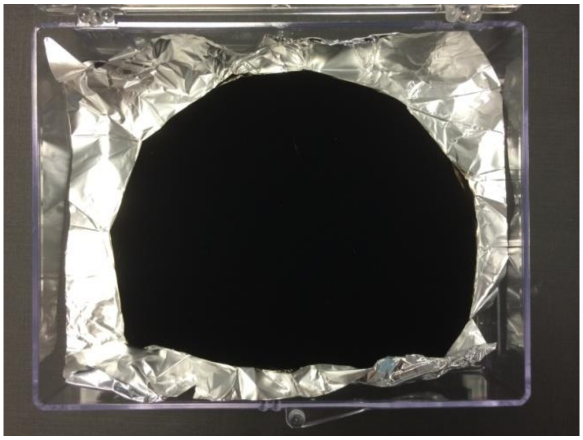

Fig. 6. Photograph of Vantablack. Image courtesy of Surrey Nanosystems.

Compared to their metal counterparts, carbon nanoparticles exhibit uniform absorbtivity across the entire light spectrum. In the following section we analyze the performance of the proposed solar thermal propulsion system.

4. Analysis and Simulation Results

Solar heat incident on the dish will heat the receiver. The heat flux incident on the receiver is dependent on the concentration ratio which is the ratio of the aperture (parabolic dish) area to receiver area. The parabolic concentrator will directly heat the propellant with the carbon nanotubes coated metal. The higher the concentration ratio, the higher the maximum temperature achieved (see Fig. 7). Higher temperatures translate into higher Isp. Temperature as a function of concentration ratio can be calculated using:

$$T_{rec} = \left(\frac{\alpha\gamma Q_{solar} C}{\varepsilon\sigma} + T_{amb}^4 \right)^{1/4} \quad (1)$$

Where α is the absorptivity of the receiver, γ is the reflectivity of the concentrator = 0.75, C is the concentration ratio. ε is the emissivity of receiver σ is the Stefan Boltzmann constant =5.67*10^{-8} W/m^{2}K^4, Q_{solar} is the solar irradiance incident on the solar panel =590 W/m^2. The maximum receiver temperature is dependent on the optical properties and the concentration ratio. It is weakly dependent on the ambient temperature implying that it would be possible to reach high temperatures even in space at low temperatures.

The maximum temperature at the absorber will theoretically never exceed the temperature of the Sun in accordance with the second law of thermodynamics. The efficiency of energy collection is greater for higher concentration ratios. The receiver (propulsion chamber) efficiency can be found using,

$$\eta_{rec} = \frac{\alpha\gamma Q_{solar} C - \varepsilon\sigma\left(T_{rec}^4 - T_{amb}^4\right)}{C Q_{solar}} \quad (2)$$

The denominator represents the heat flux incident on the parabolic concentrator. The numerator is the difference between heat incident on the receiver and heat flux lost due to radiation. The optical efficiency reduces at higher temperatures for any concentration ratio (Fig. 8, 9). As the temperature rises, the absorber changes color and starts to glow; which reduces the efficiency of light absorption. The effect of carbon nanotubes is important at higher temperatures even though the difference between the efficiency at higher temperatures for black paint and nanotubes reduces (Fig. 8). In reality the deterioration of black paint at these temperatures will reduce its efficiency. Spectral dependent efficiency of the receiver can be found using [11]:

$$\eta_{rec} = \frac{C\int \alpha(\lambda) Q_{solar}(\lambda) d\lambda - \int Q_b(\lambda, T_{rec})\alpha(\lambda) d\lambda}{C\int Q_{solar}(\lambda) d\lambda} \quad (3)$$

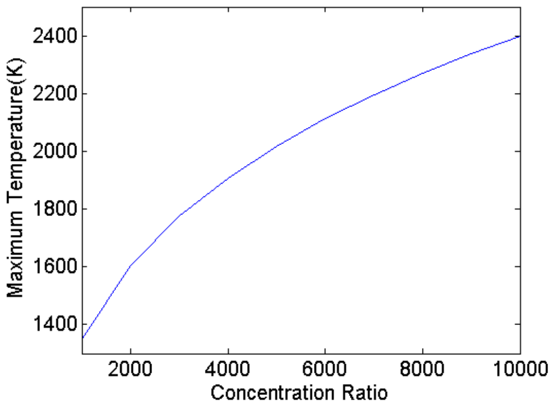

Fig. 7. Graph of concentration ratio vs maximum temperature

The thrust, F and specific impulse, Isp can be determined using equations (4) and (5). Assuming water as propellant with molecular mass, M=0.018kg/mole. The mass flow rate is assumed as 0.001 kg/s and specific heat ratio k=1.4. R is the universal gas constant. At steady state, the exhaust velocity, V_e can be calculated from [1]:

$$V_e = \sqrt{\left(\frac{2k}{2k\text{-}1}\right)\left(\frac{RT_c}{M}\right)} \tag{4}$$

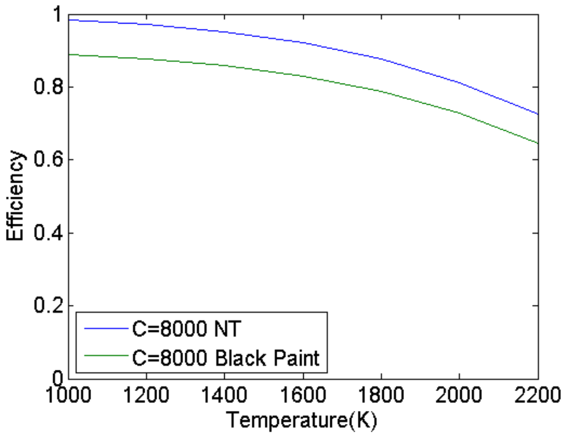

Fig. 8. Graph of absorptivity efficiency vs temperature

$$F = \dot{m}V_e \tag{5}$$

$$I_{sp} = \frac{V_e}{g} \tag{6}$$

The required Isp can be achieved by raising the exhaust temperature (Fig. 10). However, increasing temperature also reduces optical efficiency (Fig. 9). Hence, the system would achieve very low thrust at high Isp.

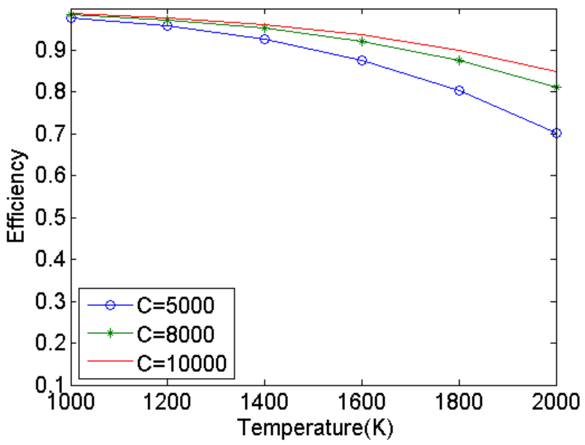

Fig. 9. Comparison of efficiency vs. temperature for various concentrations ratios.

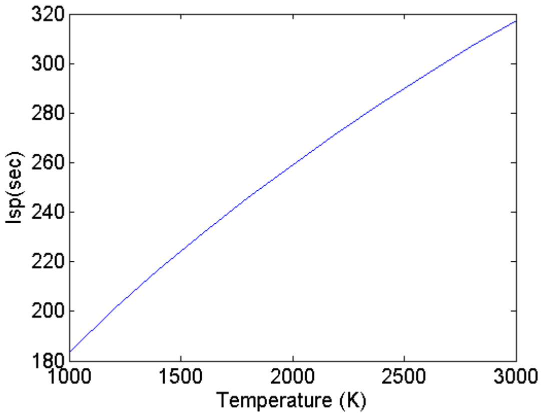

Fig. 10. Comparison of temperature achieved vs Isp.

These results suggest that there exists a design trade-off between Isp and thrust. High Isp can be achieved at low thrust, while low thrust maximizes utilization of the incoming solar energy. The ability to dial up or down the Isp and thrust performance using this system opens some interesting possibilities. The system may be operated at high Isp during transit, while at high thrust during capture orbits and gravity escape maneuvers. As seen from the results, the Isp can range from 190 s to 320 s. We compare the attainable delta-v vs dry mass ratio in Fig. 11. At Isp of 320 s, a spacecraft can achieve delta-v of 4 km/s for dry mass ratio of 0.3. This approaches the delta-v of our electrolysis propulsion system.

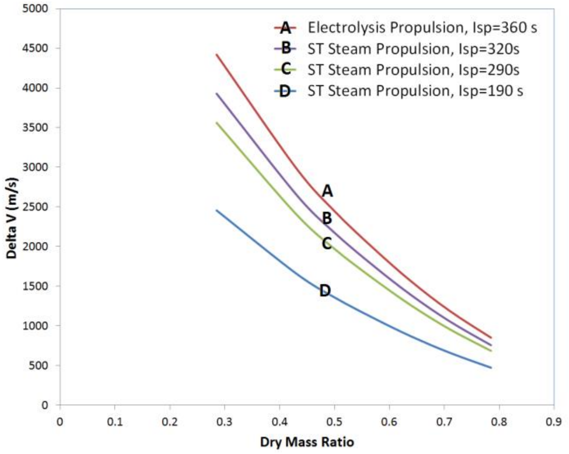

Fig. 11. Delta-v achievable for various water based propulsion systems and spacecraft dry mass ratios.

5. Feasibility Experiments

We developed simple experiments to demonstrate the capabilities of the carbon nanoparticles in collecting solar energy and converting it into heat. The heat is transferred to liquid water which becomes steam. In our experiment (Fig. 12, Table 1) a parabolic dish of concentration ratio of 3030 was manufactured. To simulate carbon nanotubes grown on the surface, carbon black nanoparticles were placed at the bottom of the test tube mixed with water.

A maximum temperature of 747 ^{o}C was achieved in this configuration. The concentration ratio will change with variation in focal length and this configuration was chosen for ease of manufacturing. Carbon based nanofluids have already proven to increase the vapor generation efficiency. The presence of nanoparticles in the volume increases thermal conductivity of the fluid, resulting in increased heat transfer efficiency. The choice of nanoparticles is important. Carbon black and graphite have properties similar to Vanta-black™.

Table 1: Experiment Parameters.

Component	Value	Units
Parabolic dish		
Diameter	0.33	m
Focal Length	0.2667	m
Reflectivity	0.7	-
Receiver		
Diameter	0.006	m
Volume of water	15	ml
Concentration Ratio	3036	-
Solar Irradiance	800-1100	W/m2

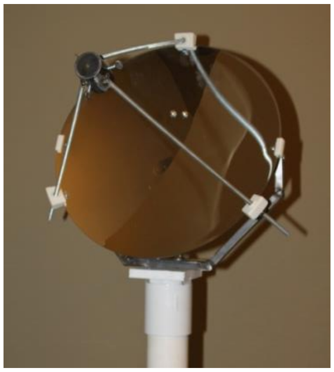

Fig. 12. Experimental setup

Experiments were performed to compare water mixed with nanoparticle and distilled water under the solar concentrator shown in Fig. 12. Carbon black nanoparticles are used for the experiments. Typical results are shown in Fig. 13. The nanoparticles accelerate heating of the water which would otherwise not be possible with the solar concentrator alone. Using the carbon nanoparticles, it was found that the time taken to boil the water was shortened by up to 15 folds.

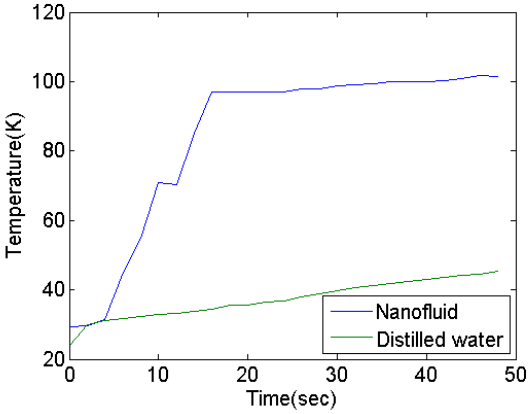

Fig.13. Comparison of distilled water and nanoparticle mixture

Once carbon nanoparticles are added to water, vapor is rapidly generated [6]. It also increases the absorption of solar light. The main purpose of the experiment was to understand the time it took to heat up the water and convert it to steam.

6. Discussion

In this paper, we proposed the use of carbon nanoparticles-coated metals to heat water into high-temperature steam. The steam would be used to generate thrust for a small spacecraft. While, solar thermal propulsion has been presented before, the use of carbon nanoparticles dramatically increases the efficiency of converting solar energy into thermal energy.

Using promising nanoparticles, such as Vantablack™ that absorbs 99.9 % of sunlight and turns it into heat, it may well be possible to overtake the efficiency of photovoltaic systems that only convert 29 to 35 % of incoming solar energy into electrical energy for electric propulsion. This will enable small, compact, spacecraft to take advantage of solar-thermal propulsion.

Our design approach also allows for solar thermal propulsion system spacecraft to move in any direction including away from the sun. This is possible by using an array of add-on reflector mirrors. To date, there has been limited work in testing solar thermal concentrators in space. Such testing is critical for the advancement of the proposed technology. Our approach shows that the technology has much promise. For example, delta-v of 4 km/s can be achieved for 12 kg CubeSat. This approaches the performance of electrolysis based systems. Advances in deployable structures, inflatables and material science can make this a reality.

Overall, solar thermal propulsion offers many advantages over mono and bi-propellants for comparable Isp performance. The return on investment of this technology comes from the strong compatibility with ISRU. ISRU will be the key to enabling sustainable space exploration and transportation. Water has been identified as the principle resources for making this possible, both on asteroids, other small bodies and Mars. However electrolysis of water containing impurities such as organic compounds, sulfur and carbon monoxide on asteroids presents a formidable challenge to the life and performance of electrolyzers. The presented solar thermal propulsion technology is immune to such impurities and is fundamentally simple.

It should be noted that solar thermal propulsion presents perhaps the simplest method to utilize in-situ resources from C-class asteroids and small bodies.

7. Conclusions

In this paper we have presented and analyzed the feasibility of a solar thermal propulsion system aided using carbon nanoparticles. The system uses water as propellant and simplifies storage and facilitates ISRU. The technology utilizes solar energy from the Sun to heat water into steam to temperatures of 1000 °C to 3000 °C. Solar energy can be absorbed at 99 % efficiency on carbon nanoparticle-coated surfaces, which is a substantial improvement over photovoltaics that can only capture between 29 and 35 % of incident solar radiation. The proposed system, unlike conventional electric propulsion systems can produce high thrust which is critical for getting capture orbit for making planetary escape maneuvers. Overall, the system is simple, contains minimal moving parts, and shows performance comparable to mono and bi-propellant propulsion systems. Fundamental experiments were carried out in the laboratory to demonstrate the capabilities of carbon nanoparticles in heating water. The results show a promising pathway towards further development of this technology.

8. Acknowledgments

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9. References

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