

Centrifugal Casting of Paraffin and Beeswax for Hybrid Rockets

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A high-level research framework is presented which seeks to navigate the barriers associated with reusing wax phase change material onboard a satellite as a hybrid rocket fuel for de-orbit or other in-space propulsion needs, while also conducting fundamental studies of the fluid mechanics and heat transfer phenomena which drive the cooling and solidification of wax within a horizontal rotating cylinder in various gravitational and thermal environments. A detailed review of past work in the area of beeswax fuel for hybrid chemical propulsion is reported and served to motivate consideration of this fuel for centrifugal casting efforts, due to previously reported values of regression rate comparable to that of paraffin wax. The production process of beeswax fuel from beekeeping detritus was perfected and documented. Analysis of the shrinkage of beeswax and the neat Candlewic FR5560 paraffin wax used herein determined a volume shrinkage percentage during liquid to solid phase transition of 18.7 ± 0.62 and $13.3 \pm 0.22\%$, respectively. An image analysis routine was developed in order to automate the process of determining the instantaneous solidification rate for each one-second timestep through the centrifugal casting process of paraffin and beeswax fuel grain sizes common for small-scale hybrid rockets. Beeswax completed solidification in 22% less time than paraffin under identical conditions but exhibited more coning of resulting solid wax. Calculated time- and space-averaged solidification rates for paraffin and beeswax were 0.017 and 0.028 mm/s, respectively, within a 50.8 mm inner diameter, 57.15 mm outer diameter, and 254 mm length polycarbonate tube. Careful analysis, however, shows that instantaneous solidification rate increases very slightly but steadily over time for both paraffin and beeswax, though the rate increase is greater for beeswax. The image analysis routine was most effective when applied to the beeswax solidification process as compared to that of paraffin, as the solid/liquid interface is considerably more salient in beeswax due to a distinct color change upon solidification. Dye will be used with paraffin casting in the future with the goal of improving solid/liquid phase contrast.

I. Nomenclature

<i>PCM</i>	=	phase change material
<i>HTPB</i>	=	hydroxyl-terminated polybutadiene
<i>LAH</i>	=	lithium aluminum hydride, LiAlH_4
<i>MMH</i>	=	monomethylhydrazine, $\text{CH}_3(\text{NH})\text{NH}_2$
<i>NTO</i>	=	nitrogen tetroxide, N_2O_4
<i>HAN</i>	=	hydroxylammonium nitrate, $(\text{NH}_3\text{OH})(\text{NO}_3)$
<i>ADN</i>	=	ammonium dinitramide, $(\text{NH}_4)(\text{N}(\text{NO}_2)_2)$

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I_{sp} = specific impulse
 fps = frames per second

II. Introduction

The Space Enabled Research Group at the Massachusetts Institute of Technology is conducting a multiyear investigation of the technology required for the repurposing of paraffin and beeswax phase change materials (PCMs) onboard satellites for utilization as fuels for in-space propulsion systems. A framework for the long-term investigation is shown in Fig. 1. Paraffin and beeswax offer low-cost, widely available, nontoxic, safe, high-performing alternatives to commonly-used in-space propellants for chemical propulsion systems. The reuse of wax PCM as a fuel for chemical propulsion inherently requires in-situ centrifugal casting – a process that would differ in important ways from Earth-based centrifugal casting efforts due to the thermodynamics that occur in a vacuum under microgravity conditions.

Wax Propulsion Project – External Inputs

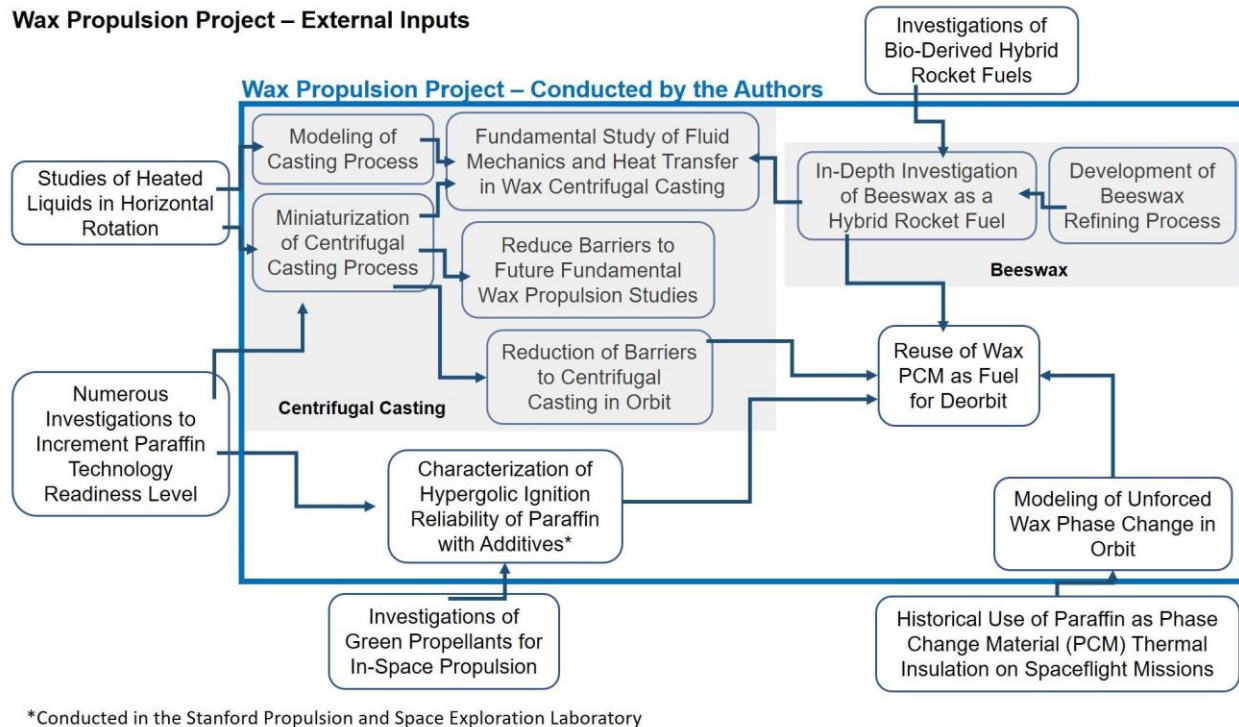


Fig. 1 Framework for long-term study of technologies required for the reuse of wax phase change materials as fuels for in-space chemical propulsion systems.

This long-term study comprises experimental and computational efforts focusing, in particular, on the centrifugal casting process of waxes in various physical environments, as shown in Fig. 2, each of which contribute to deeper understanding of casting under specific gravitational and thermal conditions, in preparation for testing on an orbital platform. The primary utility of these different experimental platforms is the ability to disentangle the unique contributions to wax cooling on the part of natural convection, forced convection, and radiation, as described in Table 1. Prior work by the authors described initial testing using the tabletop apparatus and two parabolic aircraft flights [1, 2].

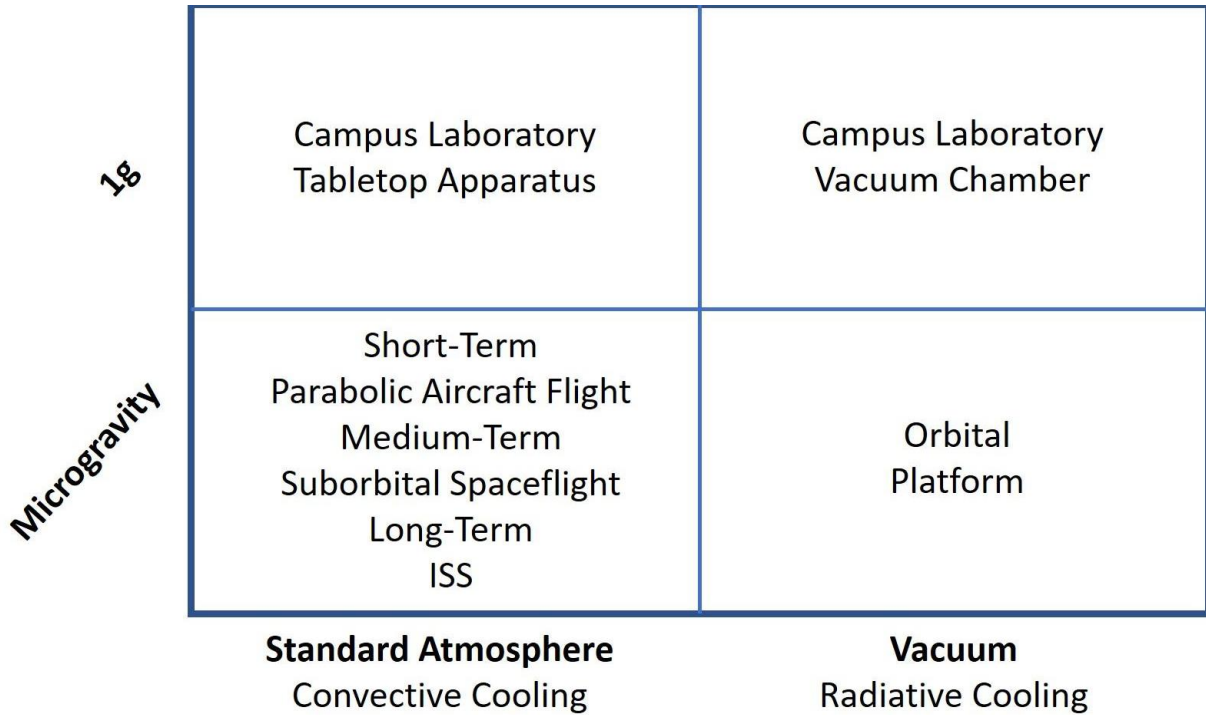


Fig. 2 Progressing complexity of experimental environments used to simulate various gravitational and thermal environments of interest in the long-term study.

Table 1 Assessment of specific heat transfer mechanism contributions to the cooling and solidification process of wax centrifugal casting in all anticipated testing environments.

	Laboratory (1 gravity)	Thermal-Vacuum Chamber (1 gravity)	ISS (microgravity)	Satellite in Orbit (microgravity)
Forced Convection	Yes	No	Yes	No
Natural Convection	Yes	No	No	No
Radiation	Yes, but with low thermal gradient	Yes, with controlled thermal gradient	Yes, but with low thermal gradient	Yes, with varying thermal gradient due to orbit
Expected Solidification Rate	Highest	Low	Intermediate	Low

The portion of this long-term study described herein relates to the centrifugal casting of paraffin and beeswax in the laboratory tabletop apparatus and the development of an image analysis routine to analyze casting results. The latter image analysis serves to automate post-processing of images acquired through the transparent acrylic endcap of the casting tube and outputs solidification distance and, ultimately, solidification rate for each timestep.

This work builds upon two decades of research in the area of paraffin- and beeswax-based hybrid rocket propulsion catalyzed by the discovery of paraffin wax as a high-performing hybrid rocket fuel by Karabeyoglu et al., followed by a wide array of fundamental and applied investigations into combustion phenomena and auxiliary technologies associated with the use of paraffin [3]. These investigations have incremented the technology readiness level sufficiently to enable (1) the development and testing of Peregrine, a sounding rocket capable of flying a 5 kg payload to 100 km altitude propelled by a paraffin-based fuel formulation and nitrous oxide, and (2) the consideration of a paraffin-based propulsion system for the Mars Ascent Vehicle of the Mars Sample Return mission operated by the NASA Jet Propulsion Laboratory [4, 5]. Notable is the absence of documented plans to use paraffin for in-space propulsion, considering the possibility of impending regulations for orbital debris mitigation which could significantly increase the number of low-Earth-orbit satellites requiring onboard propulsion. A 2013 study by DeLuca et al. considered hydroxyl-terminated polybutadiene (HTPB) and paraffin as candidate fuels for an active space debris removal mission, but eliminated paraffin due to the need for multiple burns and high mechanical strength [6, 7].

However, since that research was conducted, Narsai demonstrated improvements in paraffin mechanical strength by the addition of 2% stearic acid by mass and Stober et al. demonstrated reliable hypergolic ignition of lithium—aluminum—hydride(LAH)-doped paraffin wax [8, 9]. The latter results enable multiple restarts of paraffin and strengthen the argument for the use of paraffin as a fuel for an in-space propulsion system.

In parallel and in response to the aforementioned progression of technological maturation of paraffin as a high-performing hybrid rocket propellant, non-conventional, bio-derived hybrid rocket fuels have also been investigated, including lard, tallow, edible oils, and beeswax. Early work in this area conducted by Lyne et al. identified beeswax as a promising area of research focus due to its combination of regression rate and mechanical stability as compared to softer bio-derived fuels [10]. This work was followed by numerous others at multiple research institutions, a detailed review of which follows and suggests that further investigation into beeswax as a high-performing hybrid rocket fuel is merited.

III. Review of Literature

A. Paraffin

The use of paraffin wax as an in-space propellant follows extensive investigation of paraffin as a hybrid rocket fuel by private companies, government researchers, and academic organizations internationally, including but not limited to such varied topics as novel fuel formulations for increased performance and combustion stability, internal geometry optimization, regression rate improvements, oxidizer swirling for improved combustion efficiency, injector design, self-pressurizing oxidizer tank dynamics, the analysis of droplet formation and combustion above the solid fuel surface, fuel/oxidizer mixture ratio control, and numerical examination of radiative wall heat flux, among many others [11-19].

Independent from progress in paraffin investigations, numerous research studies focused on the search for *green propellant* alternatives to state-of-the-art in-space propellants such as hydrazine (N_2H_4), monomethylhydrazine (MMH, $\text{CH}_3(\text{NH})\text{NH}_2$), nitrogen tetroxide (NTO, N_2O_4), and strong acids, which despite high performance and decades of heritage suffer from costly toxicity, carcinogenicity, and environmental threats [20-22]. The two most investigated green propellant substitutes have been AF-M315E and LMP103S, which are hydroxylammonium nitrate (HAN, $[\text{NH}_3\text{OH}]\text{NO}_3$) and ammonium dinitramide (ADN, $[\text{NH}_4][\text{N}(\text{NO}_2)_2]$) based on liquid monopropellants, respectively [23-27]. Bi-liquid green propulsion systems have also been considered as alternatives to hydrazine and NTO, including a nitrous oxide/ethylene combination as well as energetic ionic liquids [28-30].

The earliest reviewed work that considered doping paraffin with LAH was that of DeSain et al. [31-33]. These studies examined the hypergolic ignition of LAH-doped paraffin with various oxidizers under pure oxygen environments. Following this work, Stober et al. characterized the hypergolic ignition of LAH-doped paraffin and analytical reagent grade nitric acid, among other oxidizers, at various LAH loadings in standard atmospheric conditions as well as under vacuum and up to 2.03 MPa pressures [9]. The reliable ignition of LAH and LAH-doped wax above 50% LAH loadings and at a wide range of pressures warrants deeper investigations into the use of wax as fuel for an in-space hybrid chemical propulsion system.

B. Beeswax

1) Evaluation as a Hybrid Rocket Fuel

The field of beeswax-fueled hybrid chemical propulsion is considerably underdeveloped compared to paraffin. An extensive search of literature related to beeswax hybrid rocket fuels yields a series of initial studies at the University of Tennessee, Knoxville culminating in two postgraduate theses [10, 34, 35], a series of annual senior design projects at Central Connecticut State University [36-44], and the lone peer reviewed article in the field of beeswax propulsion by the Egyptian Space Technology Centre [45]. Most of these works generally investigated a broad range of bio-derived hybrid rocket fuels, but beeswax consistently proved most practical as a hybrid rocket fuel.

In the earliest available work on the topic known to the authors, Lyne et al. point out that the energy densities of lard, tallow, partially hydrogenated coconut oil, and beeswax are comparable to traditional hydrocarbon fuels, but focus the study on theoretical combustion temperature and specific impulse, mechanical strength, and regression rate of paraffin, lard, beeswax, and some select mixtures thereof [10]. Nineteen successful hot fires with gaseous oxygen were conducted of 7 to 10 s burn times with 12.7 and 25.4 mm fuel grain port diameters. Beeswax exhibited mechanical strength superior to lard (which was consistently subject to spallation) and experimentally-determined time- and space-averaged regression rates as a function of oxidizer mass flux were on par with paraffin wax.

Scholes contributed considerable experimental data on beeswax combustion beyond the original work of Lyne, resulting in regression rates for beeswax higher than those reported for paraffin [3] at all tested oxidizer fluxes (approximately 3-10 g/cm²s) [34]. Putnam expanded the research to include combustion experiments with nitrous

oxide as an oxidizer and theoretical analyses of aluminum powder as an additive to beeswax fuel [35]. Analytical results suggested that the addition of 20% aluminum powder to beeswax burning with gaseous oxygen improved the specific impulse by about 1% at both 1.03 and 3.45 MPa chamber pressures, though nozzle area ratios were not specified. Experimental results reaffirmed regression rates for pure beeswax burning with gaseous oxygen consistently higher than or equal to those reported for paraffin [3] at all tested oxidizer fluxes (3.5-6.5 g/cm²s).

A series of studies by Naoumov et al. from 2013 to 2020 attempted to establish regression rate comparisons between paraffin, beeswax, and each of these with up to 10% micron-sized aluminum powder added for fuel grain port diameters of 12.7, 25.4, and 38.1 mm at combustion chamber pressures of 0.448 to 0.965 MPa [36-44]. Over 150 hot fires were conducted with gaseous oxygen alongside theoretical thermodynamic calculations which showed (1) little influence of aluminum addition on regression rate, (2) experimentally-determined regression rates of beeswax above those for paraffin reported by Karabeyoglu [3] but below those for beeswax reported by Putnam [35] at similar conditions; namely, oxidizer mass fluxes between 0.7 and 1.75 g/cm²s. Experimental efforts in these studies were plagued with low oxidizer mass flow rates (0.5-0.95 equivalence ratios), though in the most recent work attempts at increasing the mass flow rate of gaseous oxygen proved successful [44]. An idiosyncrasy of this series of studies is the novel attempt to estimate unburned fuel losses using thermocouples placed downstream of the nozzle exit, predominantly discussed in Naoumov 2015 [39]. The publication most focused on beeswax and beeswax with aluminum additive results is that of Naoumov 2016a [40]. Throughout this series of studies, fuel grains were drip casted and geometric voids were observed, though improvements in the drip casting process were noted by Naoumov 2020 [44] which were characterized by low-conductivity casting materials housing the solidifying wax.

Most recently, Makled investigated regression rates in beeswax burning with gaseous oxygen [45]. This work differs from that of Naoumov in that significantly higher oxidizer mass fluxes were used, in part due to initial port diameters of 7 mm. Over a 12 to 15 g/cm²s range of oxidizer mass fluxes, Makled reported space- and time-averaged beeswax regression rates between 1.4 and 1.6 mm/s. Also of note is the drip casting process used, which leveraged extremely slow cooling to reduce voids and x-ray scans of the casted fuel grain in order to ensure adequately casted grains.

2) In the Context of Non-Propulsion Space Exploration Efforts

In parallel to applied research on the use of beeswax as a hybrid rocket propellant in the near term, some researchers are separately considering the utility of bees as pollinators in far-future off-Earth agricultural efforts. The potential establishment of beeswax as a viable alternative to state-of-the-art rocket fuels would add merit to the idea of using honey bees to pollinate, thereby yielding honey and wax for consumption and fuel, respectively. Motivated by this futuristic concept, various researchers have attempted to understand the behavior of bees in microgravity. Vandenberg et al. developed a honey bee experiment which flew onboard STS-41-C in 1984 in order to assess survivability as well as behavior and comb-building activity of western honey bees, *Apis mellifera*, in the long-term microgravity environment [46, 47]. This experiment housed roughly 3400 worker bees and one queen over a seven-day spaceflight mission and resulted in the bees' moderate adaptation to the microgravity environment including comb construction and flying without collisions after several days of adjustment, as well as less than 1.5% bee mortality. Comb geometries differed significantly from those on Earth, but the queen was still able to lay eggs in orbit.

MIT researchers unaffiliated with the authors launched approximately 40 bees on a suborbital spaceflight onboard a Blue Origin New Shepard rocket, NS-11, in early 2019, including two fertilized queen bees while keeping two fertilized queen bees on Earth as a control group in order to understand the effect microgravity flights have on bee behavior after returning to their native environment [48, 49]. Publication of the results of that flight are still pending. Stasiowska flew *A. mellifera* onboard two low-altitude sounding rockets with significant g-loadings, used environmental measurements to infer bee behavior, and encountered significantly greater mortality rates compared to Vandenberg (up to 50% on one flight) which they attributed to the absence of a queen and the impact of vehicle vibrations [50].

IV. Technical Approach

The review of literature suggested that continued focus on beeswax was warranted as a high-regression-rate fuel for chemical propulsion systems. Therefore, a reliable method of beeswax production which facilitated repeatable batches was developed, and beeswax was included alongside paraffin in drip casting and centrifugal casting efforts described herein.

A. Beeswax Refinement and Chemistry

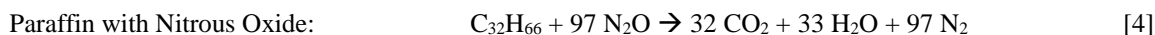
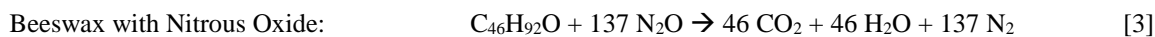
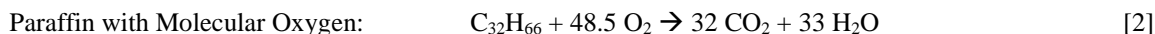
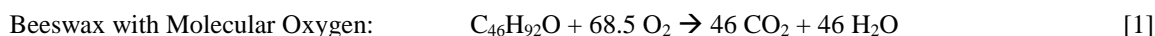
The production of beeswax for the research described herein began with beekeeping detritus sourced in collaboration with the Urban Beekeeping Laboratory and Bee Sanctuary, an affiliated non-profit research arm of the

Best Bees Company of Boston, Massachusetts [51, 52]. This organization provided the detritus at no cost, as they would typically expend resources to compost the wax. The detritus comprised three forms of waste wax from beekeeping: capping, honeycomb, and brood comb wax. Capping wax – the white, almost pure wax used by bees to cover their honeycomb – is the wax that produces the highest yield as measured by resulting mass of usable fuel and is most often used in the production of commercial-grade beeswax. Both regular comb wax, where bees store their honey, and brood comb, where bees store their larvae, also contain some amount of usable wax as well as honey, bees (both dead and alive), waste, and other living organisms.

The wax refined in this study was processed from this state utilizing a double filtration process common in small-scale beeswax production [52]. The detritus was immersed in water and left to sit sealed overnight to remove residual honey and terminate any remaining living organisms, thereby making it safer with which to work. The detritus was then placed into boiling water and allowed to melt completely in a melting pot. The melting pot was turned off after the wax had completely melted and allowed to cool completely overnight. When the wax resolidifies, it remains separate from the water and forms a wax cake at the top of the melting pot. The slower the wax is allowed to cool, the more sediment will be able to settle at the bottom of the pot, thereby producing a cleaner wax cake. This process aids in separating the majority of unusable waste from the wax. This waste, also known as slumgum, is commonly used as a firestarter or fertilizer. The wax cake can be pressed down and removed from the melting pot. Note that the bottom of the wax cake will have additional sediment, mostly comprising pollen. This sediment can be scraped off and discarded to make the next step of filtration easier.

The second filtration does not require the wax to be melted in water and can be conducted in a dry melting pot. It is important to monitor the temperature of the wax as it is melted, as heating the wax above 85 °C risks discoloration of the wax and the flash point lies slightly above 250 °C [53]. Once the wax is fully melted, it is poured through a 5 µm mesh size filter sheet to remove the last of the sediment from the usable beeswax. It is important to pour the wax into a container that can be manipulated, such as a silicon mold or a plastic tub, to aid in the later removal of the wax. The 5 µm mesh size filter was chosen at the direction of [51] to allow only the wax through. This filtration step can be repeated as many times as necessary to achieve adequately clean wax and is also useful in refiltering wax contaminated by dirt or similarly-sized particles in the laboratory setting.

The resulting beeswax is a highly-complex composite of over 300 unique chemical compounds including esters (67%), hydrocarbons (14%), free acids (12%), alcohols (1%), and other substances [54, 55, 56]. These proportions correspond to beeswax produced from *A. mellifera* (western honey bee), the most common species of honey bee globally, and exact chemical composition may vary slightly based on environmental factors [56]. In particular, the beeswax chemical composition literature reports a large presence of triacontanol ($\text{CH}_3(\text{CH}_2)_{29}\text{OH}$; up to 65%, per Putnam [35]), a molecule with extraordinary similarities to the paraffin wax used in this study as well as many prior studies, $\text{CH}_3(\text{CH}_2)_{30}\text{CH}_3$. An average chemical formula for beeswax used by Putnam and Naoumov is $\text{C}_{46}\text{H}_{92}\text{O}$, with molecular mass of 661.2 g/mol [35, 40]. Using this chemical formula, the stoichiometric global reactions for the combustion of beeswax and paraffin with molecular oxygen and nitrous oxide are shown in Reactions [1-4].



The corresponding oxidizer-to-fuel mass ratios for these four reactions are 3.32, 3.44, 9.12, and 9.47, respectively. A careful analysis of the percent reduction in volume was conducted in order to ensure that casting tubes were properly filled with liquid immediately prior to casting with the goal of producing a solid wax fuel grain with an outer to inner diameter ratio of 2 corresponding to a 75% volume fill factor. For these shrinkage observations, known volumes of each wax were poured into a beaker and allowed to cool and solidify, yielding a considerable meniscus. The meniscus was filled with a carefully measured quantity of water equal to the displaced volume of wax due to solidification. This process resulted in volume reduction percentages of $13.3 \pm 0.22\%$ and $18.7 \pm 0.62\%$ for paraffin and beeswax, respectively, resulting in liquid volumetric fill factors at the onset of centrifugal casting of 86.5 and 93.4%. The melting temperatures of beeswax and paraffin are reported as 63-65 °C and 68-70 °C, respectively [56, 9].

B. Drip Casting vs. Centrifugal Casting

While centrifugal casting of paraffin wax has become commonplace due to a desire to produce a fuel grain absent of voids and cracks, no evidence was found in the literature of prior efforts to investigate the formation of beeswax into annular fuel grain geometries, either by drip or centrifugal casting. Therefore, a side-by-side drip casting comparison was carried out and is shown in Figs. 3 and 4 for paraffin and beeswax, respectively. For each of these cases, a 50.8 mm inner diameter polycarbonate tube was filled with liquid wax at approximately 80 °C and a mandrel of 25.4 mm diameter placed at the center of the drip casting tube.

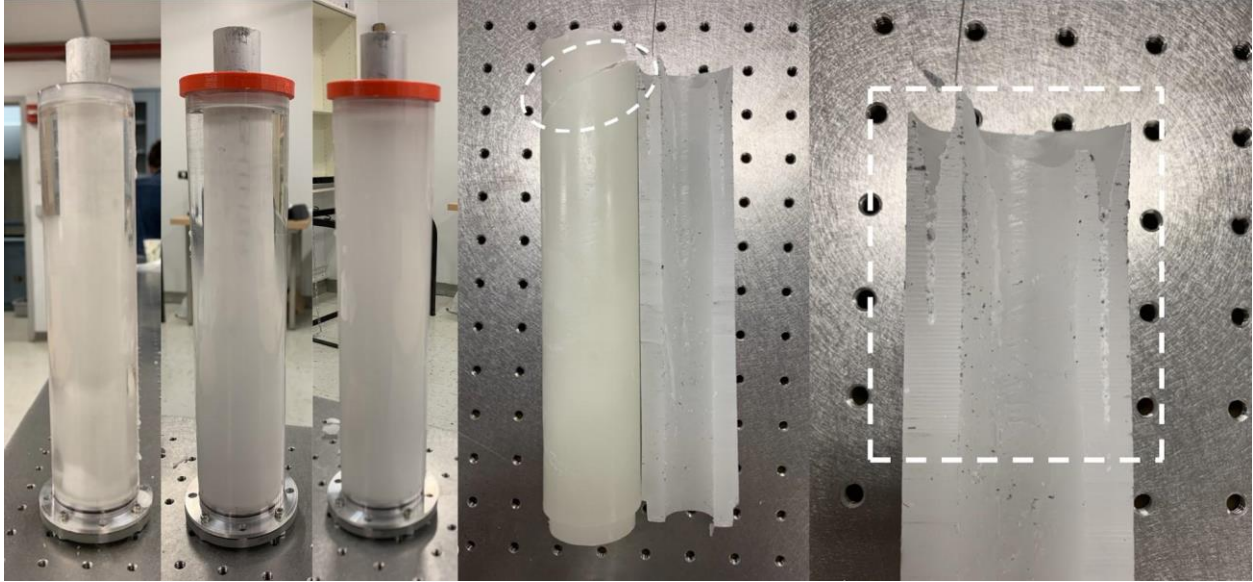


Fig. 3 Drip casting process of paraffin showing phase change and resulting voids much deeper into the geometry than would be obvious to an observer from simple handling.

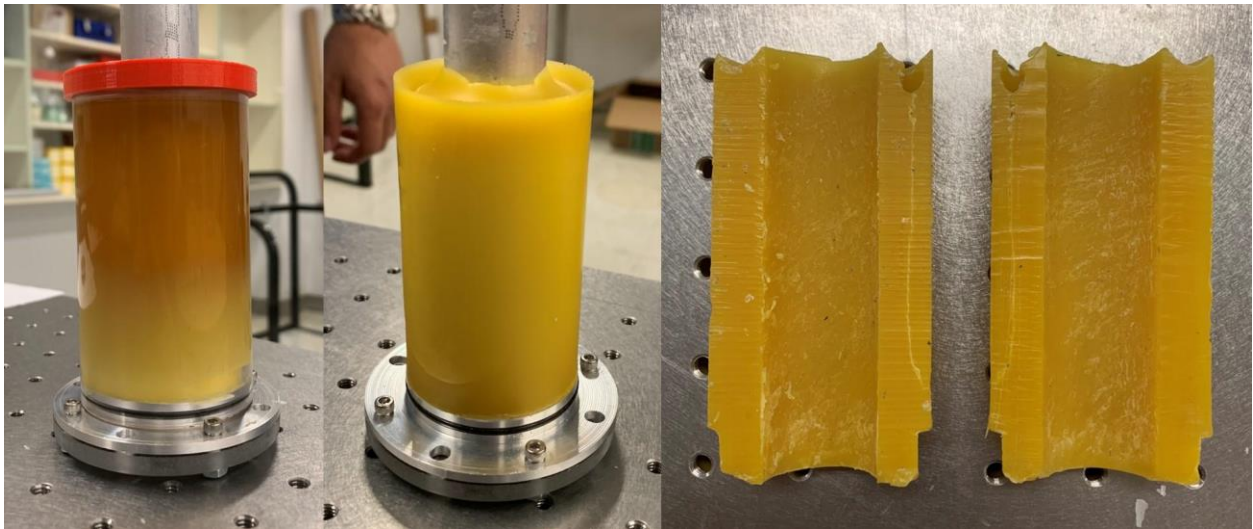


Fig. 4 Drip casting process of beeswax showing that beeswax is generally susceptible to similar voids as compared to drip casted paraffin.

Figures 3 and 4 illustrate that both paraffin and beeswax are susceptible to voids due to volume reduction during solidification. Previous work by author Stober attempted to address void production during drip casting by breaking down the drip casting process into a series of smaller casts, but cracks and voids were still produced, as seen in Fig. 5. Taken together, Figs. 3-5 shows the justification for centrifugal casting, as solidified wax is continuously deposited on the outermost point in can reach via centrifugal forces, thereby mitigating void production.

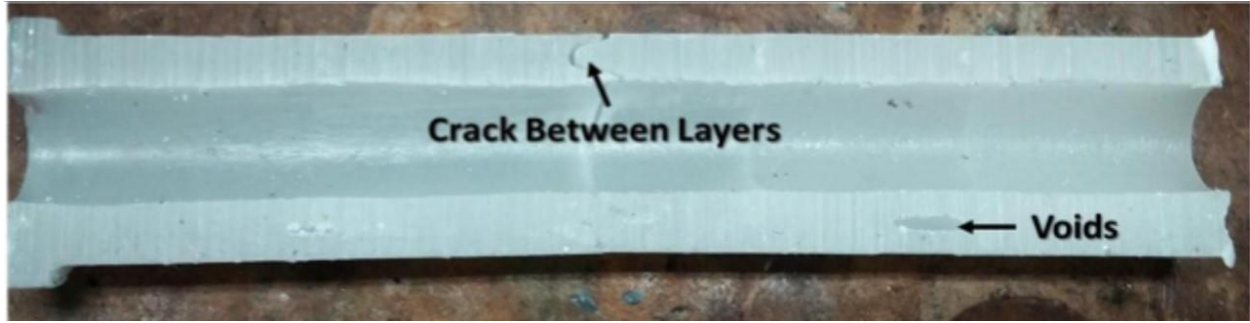


Fig. 5 Drip casted paraffin fuel grain casted in five roughly equal heights (left to right) using a mold and mandrel exhibiting cracks and voids due to volume reduction upon solidification.

To facilitate the centrifugal casting process in the laboratory, an experimental setup was designed and constructed which comprised t-slotted framing for stability and ease of alignment, a DC motor controlled by an Arduino and driving the casting tube via an aluminum interface plate (the *fore* end). At the aft end of the casting tube, an aluminum ring holds an acrylic window for viewing the progression of the wax solidification front. A protruding from the aft end window engages a linear bearing which is mounted on the t-slotted framing and stabilizes the aft end. Casting tubes were variously made of 3.175 mm thick aluminum or polycarbonate, depending on the goals of the particular test. Aluminum exhibits thermal conductivity four orders of magnitude greater than polycarbonate (154 W/mK vs. 0.2 W/mK [57, 58]), but polycarbonate has the advantage of optical transparency. Therefore, polycarbonate is used on all early tests where the image analysis routine is being developed, including those described herein. Ultimately, identical tests will be run with aluminum exchanged for polycarbonate which will aid in the isolation of the influence of thermal conductivity on solidification rate.

Prior work by the authors determined the time to form an annulus as a function of rotation rate for water, SAE 5W-30 motor oil, and liquid paraffin wax in 1g and in microgravity [2]. The paraffin results for a grain geometry identical to the current study are repeated in Fig. 6. From this data, a rotation rate of 1850 RPM was chosen. The time taken to form an annulus was not so relevant as was the assurance that we were well above the critical threshold to maintain a smooth annulus.

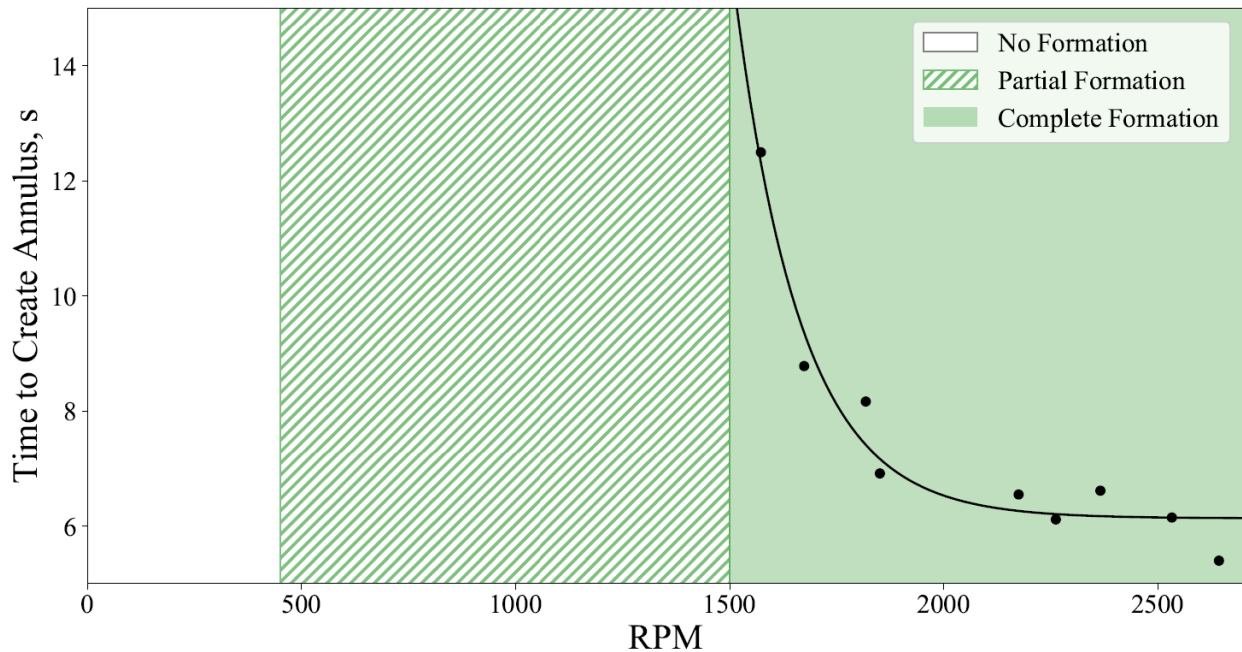


Fig. 6 Result from a prior study by the authors [2] showing the ability of liquid paraffin to form a smooth annulus at various rotation rates for an identical geometric and environmental case to that studied herein.

Figure 7, also from a prior study by the authors, shows the progression of turbulent to laminar flow as the rotation rate of liquefied paraffin is accelerated from 1450 to 1700 RPM. The formation of a smooth annulus followed about 10 to 15 s after sending the rotation rate increase command. Figure 7d) shows the state of paraffin wax immediately prior to beginning optical data acquisition for the image analysis described herein. Prior to this moment, paraffin was melted in a heating pot to approximately 110 °C, poured into the tube up to a marked fill line (which is positioned based on the aforementioned shrinkage analysis), and installed on the test rig. The time between initial opening of the melting pot flow valve and beginning of casting tube rotation was approximately two minutes, and the average temperature of paraffin at onset of rotation was always above the melting temperature, as only rarely small amounts of paraffin adjacent to highly-thermally-conductive aluminum parts had solidified prior to rotation but always re-melted immediately.

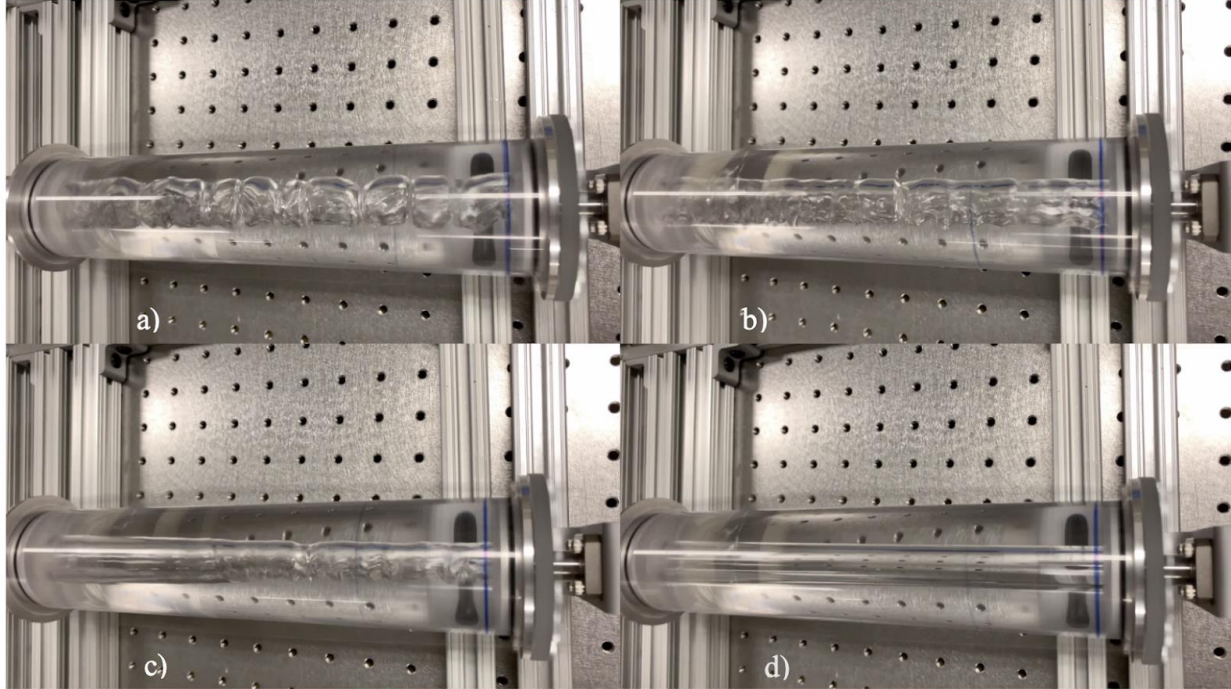


Fig. 7 Progression of smooth annulus formation in liquefied paraffin wax as the rotation rate is increased from 1450 to 1700 RPM.

C. Wax Solidification Imagery Analysis

In order to determine the behavior of both beeswax and paraffin wax in the centrifugal casting chamber, two videos were taken with a GoPro HERO 7 Black at 60 frames per second (fps) and an image analysis script was created in Python to evaluate the rate at which the wax solidified. Individual frames were binarized to differentiate between the solidified and liquid wax and a length of solidification in units of number of pixels was obtained from these binarized frames. A preliminary analysis revealed that using only one fps significantly reduced computation time without causing a reduction in accuracy. A pixels-to-physical-distance scale conversion factor was obtained by averaging the pixel values obtained from the o-ring groove present on the face of the solidification chamber, as the width of the o-ring groove is known a priori.

There is slight ambiguity in tracking the solidification front because there are sometimes two interfaces observed. The authors hypothesize the presence of solid, liquid, and semisolid phases in paraffin and beeswax based on observations of numerous centrifugal casting experiments. Therefore, the interface between liquid and semisolid is termed the *leading edge* solidification front, while the interface between solid and semisolid is termed the *trailing edge* solidification front. The presence of two solidification fronts is particularly salient in beeswax casting due to significant color differences between these three proposed phases – a fact that reduces noise in image analysis results as compared to those for paraffin. The existence of multiple solidification fronts is congruent with aforementioned literature which posits that beeswax is a composite of over 300 chemical constituents, certainly with varying melting temperatures that would cause portions to soften before others. Examples of the solidification process as viewed

through the aft window can be seen in Figs. 8 and 9, where the trailing and leading edge solidification fronts are visible, respectively.

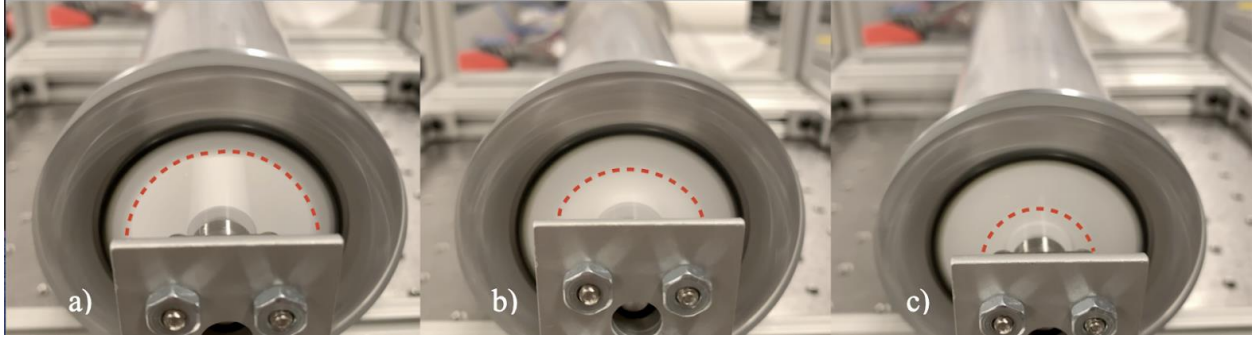


Fig. 8 Solidification of paraffin wax during the centrifugal casting process showing the progression of the trailing edge solidification front (red dotted line) migrating radially inward, as is the case for all tests.

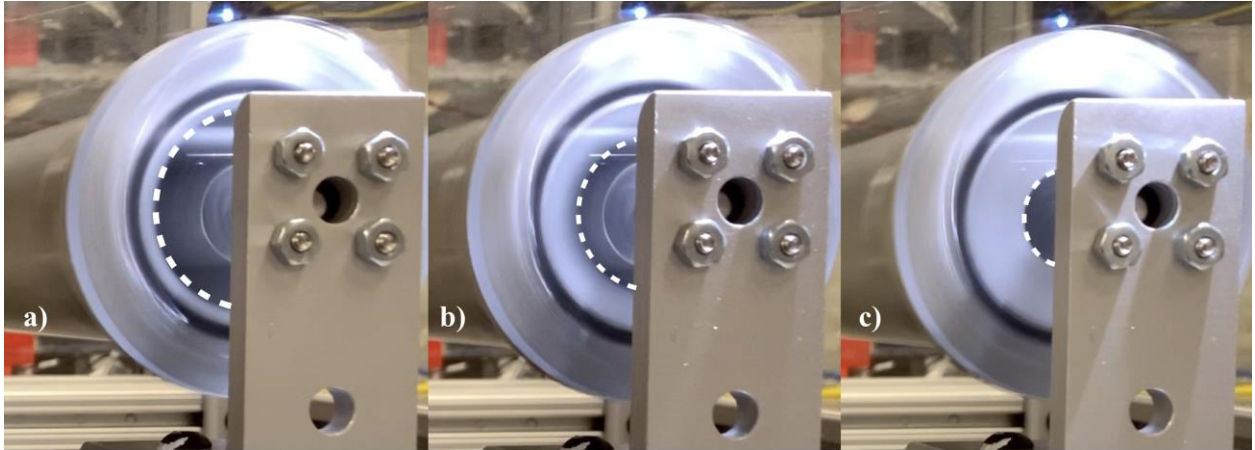


Fig. 9 Solidification of paraffin wax during the centrifugal casting process showing the progression of the leading edge solidification front (white dotted line) migrating radially inward.

Note that the difference between the semisolid and liquid phase could be described as one of opacity, while the difference between the semisolid and solid phase could be described as one of color. This fact causes the Python routine to most easily track the *leading edge* solidification front. Therefore, all results presented here correspond to that front. Examples of the binarized images for beeswax are shown in Fig. 10 and comprise a series of 12 frames, each spaced 1 minute apart in the solidification process. The o-ring groove where the aforementioned conversion factor is obtained can be seen as the first black band in each frame. The white region immediately radially inward from the o-ring is partially comprised of an aluminum lip, seen also in Fig. 9, as well as the solidified wax up to the leading edge solidification front. The aluminum lip exhibits a constant pixel count in each frame which can be subtracted from the total white pixels counted leaving only the number of pixels representing solid wax. Full solidification in Fig. 10 occurs after about 10 minutes time.

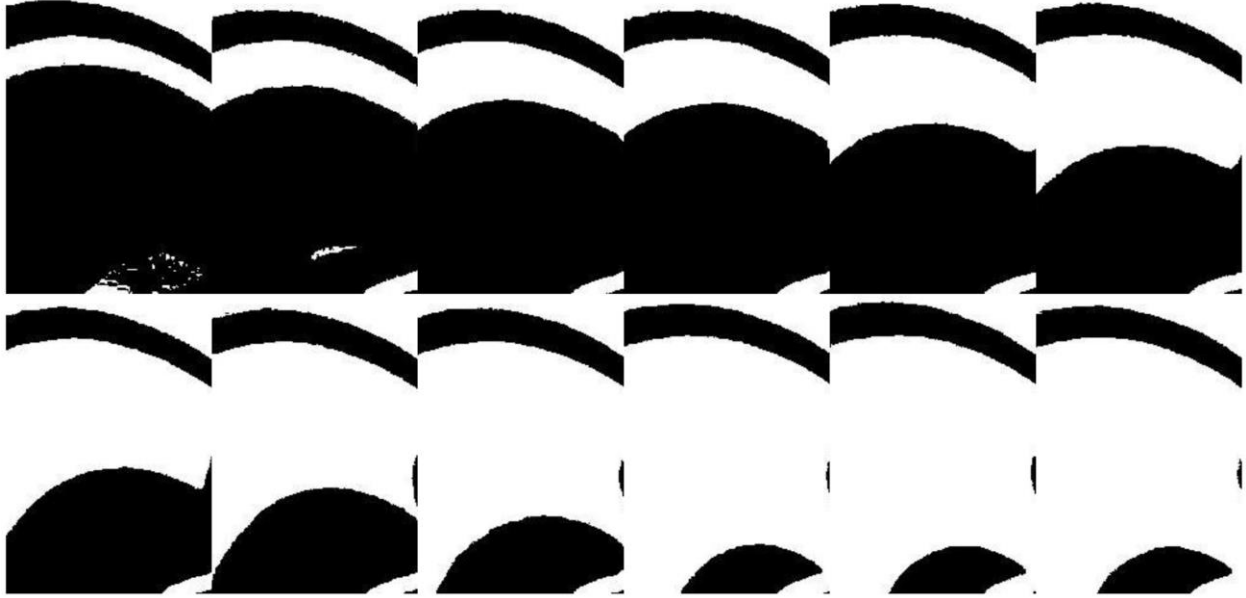


Fig. 10 Binarization of the upper region of the solidification chamber displaying the solidification process of beeswax. Each image displays data from one additional minute after onset of rotation.

V. Results

The solidification process can be seen in Fig. 11 for both the beeswax and paraffin. Because beeswax has a distinguishable color difference between liquid and semisolid phases (light yellow semisolid beeswax vs. medium brown liquid beeswax, evident in Fig. 4), it was easy for the image analysis routine to accurately calculate distance solidified. Note that two brief decreases in the solidification of beeswax can be seen in Fig. 11a and are a result of momentary spin down and spin up of the driving DC motor in order to understand impact on solidification rate. In both cases, the wax remelts – a result that is not an artifact of the image analysis, as it can clearly be seen in captured video.

The solidification process for paraffin wax, shown in Fig. 11b, however, was considerably more difficult to measure due to the relative transparency of paraffin wax in a liquid state and the tendency of the wax to diffuse light, even through extremely thin solidified slivers, which resulted in inconsistent ambient lighting within the chamber. To address this, the video was divided into two temporal phases, the first encompassing the initial six minutes of solidification and the second encompassing the remainder of captured video. The solidification was determined for these two videos in the horizontal and vertical directions, respectively. Due to parallax caused by the image acquisition setup, data from the initial six minutes needed to be multiplied by a constant correction factor of 1.23 representing the ratio of pixel sizes from the leftward and upward directions. That is, pixels located directly above the center of the casting tube represent a larger true area than pixels located directly to the left of the center of the casting tube, an artifact of the experimental setup geometry and camera placement which is accounted for via the correction factor.

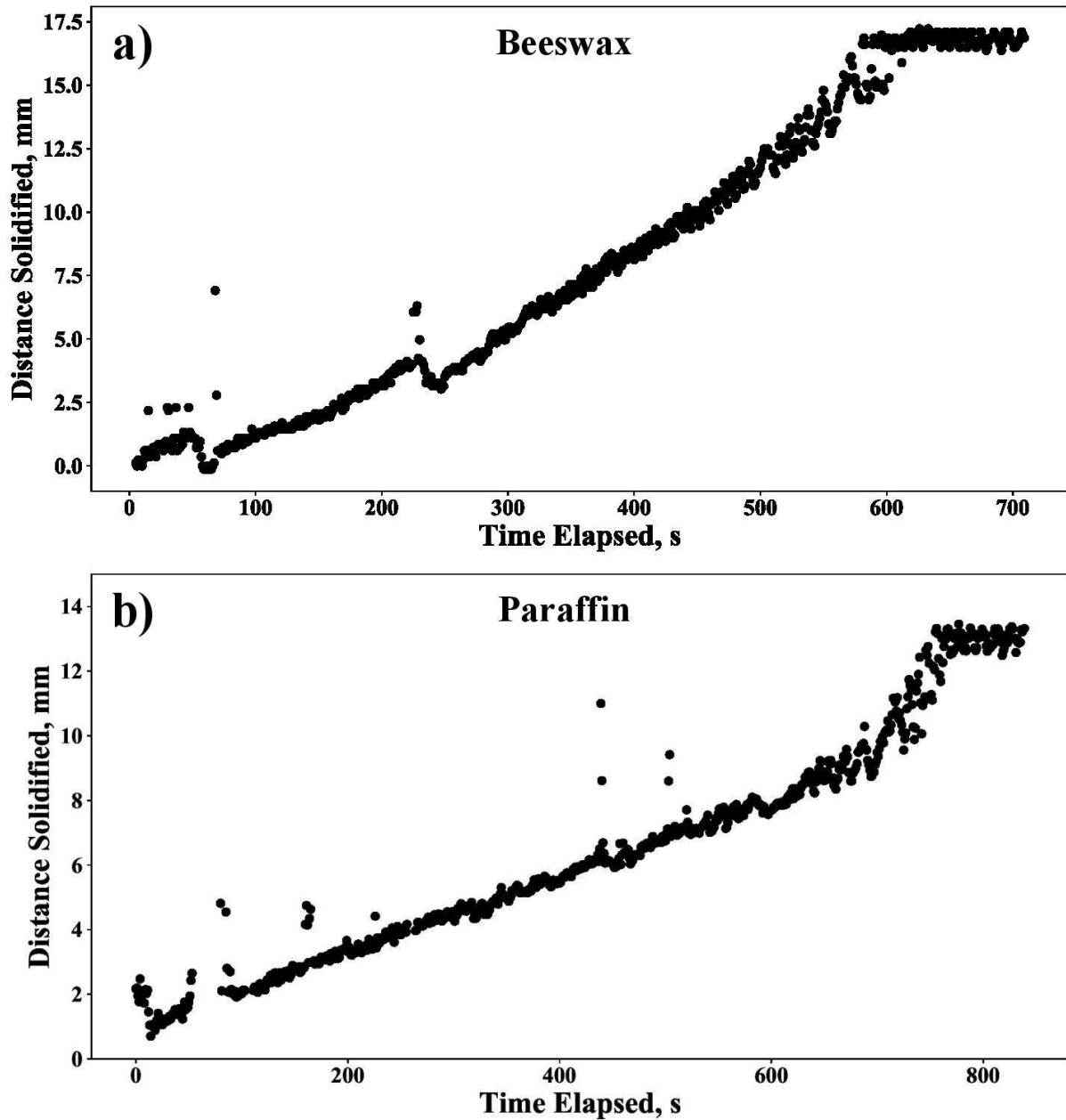


Figure 11 Solidification process of a) beeswax and b) paraffin wax resulting from the Python-based image analysis code developed herein. Each test was characterized by a 50.4 mm inner diameter, 254 mm length polycarbonate casting tube of 3.175 mm thickness and rotation rates in excess of 1500 RPM. Noise in paraffin results caused by ambient lighting effects which uniquely impacted paraffin phase contrast.

From Fig. 11, it's clear that beeswax completed its solidification in approximately 22% less time than paraffin under identical conditions, despite having to cover a 29% farther solidification distance due to coning. This was because the final inner diameters of beeswax and paraffin were approximately 17 and 25 mm instead of the ideal 25.4 mm. This is caused by heat leaving the endcaps and allowing greater solidification at the longitudinal ends of the fuel grain as compared to the center. Figure 12 shows the cross-sectional view of the paraffin fuel grain that resulted from the casting plotted in Fig. 11b. Recall that the fore end cap is completely aluminum and the aft end cap is an aluminum

ring holding up an acrylic window as viewed in Figs. 8 and 9. The presence of aluminum on each end cap provides an exit path for heat leading to non-uniformities in fuel grain inner diameter. Furthermore, the simple existence of an endcap, no matter the material, causes the 1D assumption of wax solidification to never be fully accurate. In the best case scenario, the endcap material has infinite thermal resistance, leading to the 1D assumption holding and identical annular cross sections at each longitudinal station. In the worst case scenario, the endcap comprises a material with zero thermal resistance and wax preferentially solidifies at the endcaps, sealing them off and leaving a hollow cavity in the longitudinal center of the resulting fuel grain. The actual endcap is closer to the best case scenario than worse, as acrylic exhibits a very low thermal conductivity nearly identical to polycarbonate at 0.2 W/mK [59].

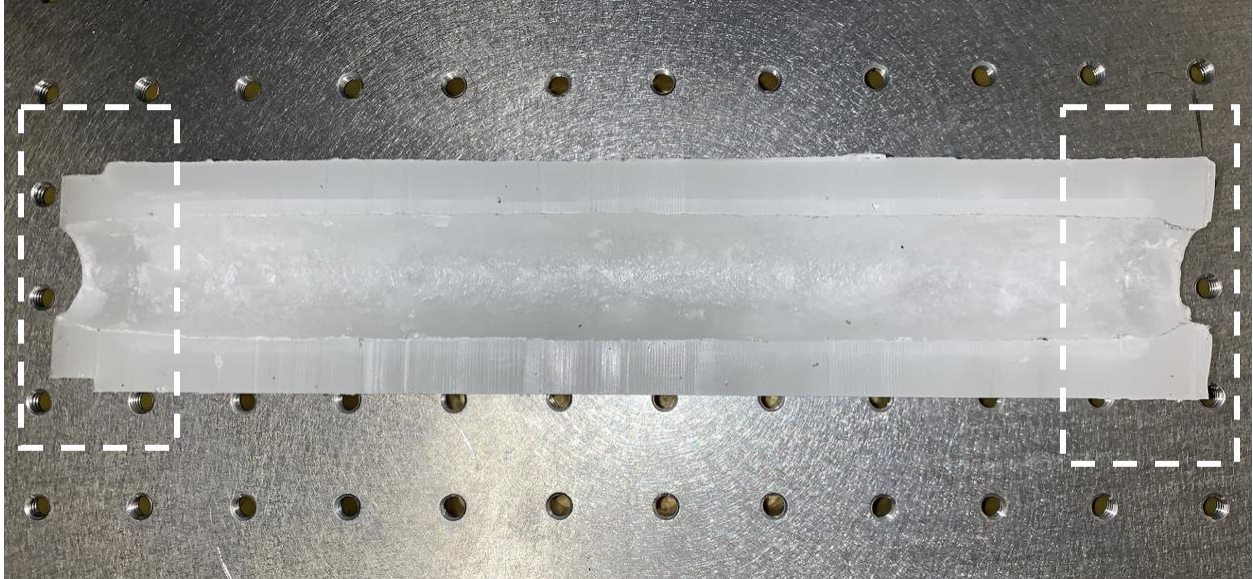


Fig. 12 Cross-sectional view of annular paraffin wax fuel grain after centrifugal casting at 1850 RPM illustrating coning at each longitudinal edge caused by heat escaping the through the endcaps.

From Fig. 11, the total trajectory of solidification for beeswax is approximately 16.7 mm in 600 s, while that for paraffin is 12.9 mm in 765 s. From these values, a time- and space-averaged solidification rate for beeswax and paraffin is calculated as 0.028 and 0.017 mm/s, respectively. That is, on average, the radial accumulation rate of solid wax in the casting tube was 65% greater for beeswax at any given moment as compared to paraffin. In order to determine instantaneous solidification rate, the raw data from Fig. 11 was differentiated. As expected, this yielded highly noisy solidification rate results. Binning schemes which averaged the instantaneous solidification rate over 10 and 50 data points were executed and compared to the unbinning solidification rate. Ultimately, binning by 10 optimally smoothed the data without excessively removing informative data points. Figure 13 shows the instantaneous solidification rates of beeswax and paraffin over the entire centrifugal casting process.

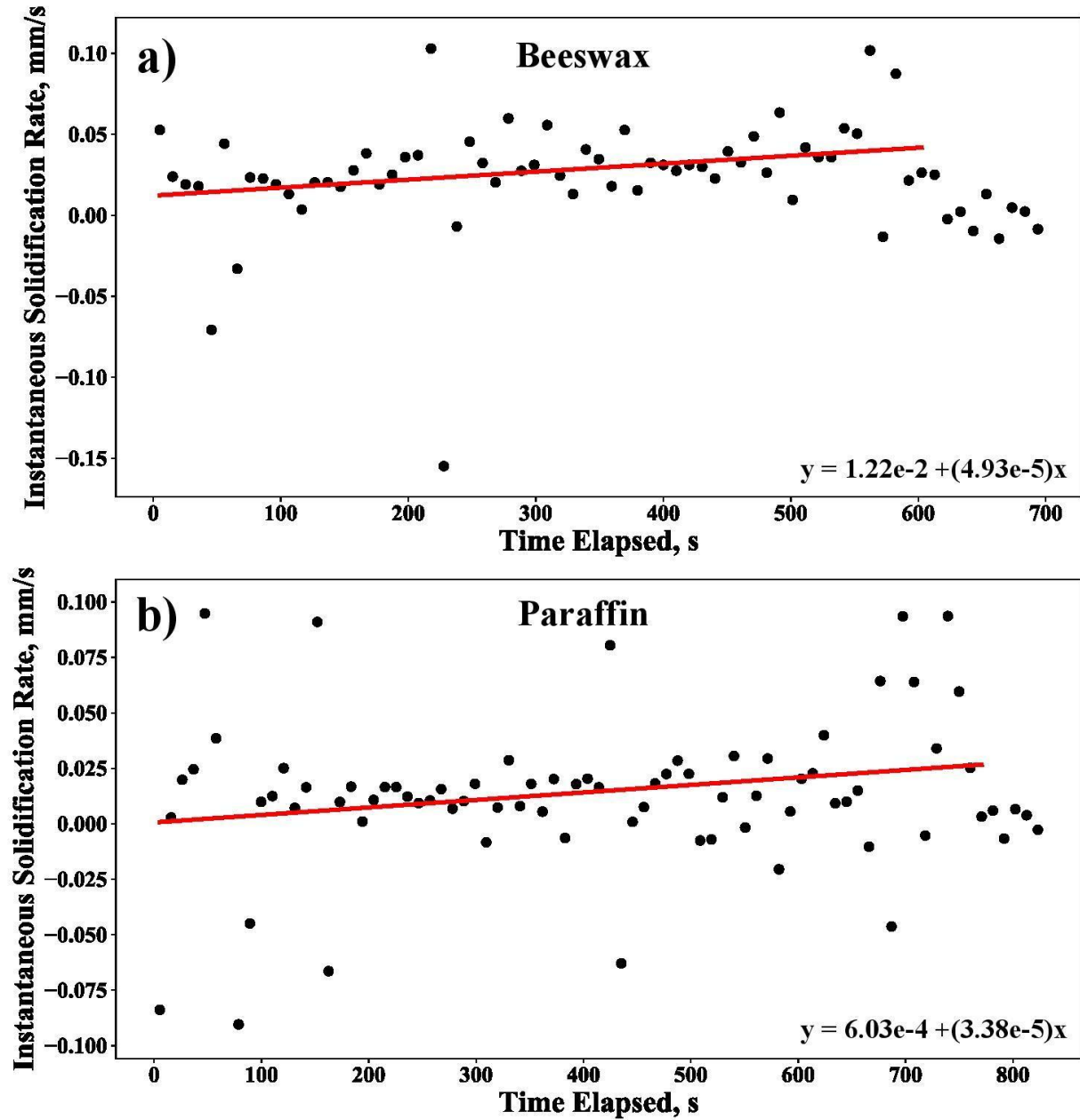


Fig. 13 Instantaneous solidification rates for a) beeswax and b) paraffin wax during the centrifugal casting process, determined by differentiating raw data output from the Python-based image analysis routine and binning by 10. Each test was characterized by a 50.4 mm inner diameter, 254 mm length polycarbonate casting tube of 3.175 mm thickness and rotation rates of 1850 RPM. Noise in paraffin results are caused by ambient lighting effects which uniquely impacted paraffin phase contrast.

Figure 13 illustrates the gradual and steady increase of solidification rate over time observed during the centrifugal casting tests. The trend was somewhat surprising to the authors. In the earlier portions of the centrifugal casting process, there is a greater solid/liquid interface surface area through which heat can escape as compared to later in the casting process. However, later in the process a greater portion of the wax mass is in the solid phase, which exhibits approximately 50% greater thermal conductivity than the liquid phase, accelerating the expulsion of heat from the

center of the fuel grain. These two phenomena have opposite influences on the solidification rate with time, but it appears that the latter effect dominates and solidification accelerates with time, albeit slightly.

VI. Conclusions and Future Work

An overarching research framework was presented which builds upon existing literature with the long-term goal of reusing wax phase change material onboard a satellite as a fuel for an in-space propulsion system. This research agenda includes fundamental and applied, experimental and computational studies and includes the contributions of expert collaborators. The current phase of study lies in the area of centrifugal casting in multiple gravitational and thermal environments and gaining understanding in the fundamentals of beeswax fuel; while upcoming work will focus on on-orbit heat transfer simulations and hot fires within a small-scale experimental rig.

An extensive literature review of paraffin and beeswax as hybrid rocket propellants was carried out which suggested that further research into beeswax performance was merited based on favorable reported regression rates with gaseous oxygen, albeit at very low oxidizer fluxes. A beeswax refinement process was developed under the guidance of experts and perfected in the laboratory. The beeswax refinement process took beekeeping waste destined for a composting facility and converted it to hybrid rocket fuel which was then used throughout centrifugal casting studies and is planned for use in side-by-side combustion studies with paraffin in the future. Beeswax and paraffin wax volume shrinkage during phase change from liquid to solid was carefully evaluated in order to inform filling fractions of the casting tube with liquid wax and reliably produce solid wax fuel grains with customary 2:1 outer-to-inner diameter ratios.

Numerous centrifugal casting experiments were run on a tabletop setup in the laboratory with paraffin and beeswax in form factors congruent with small-scale hybrid rockets, two of which were selected for analysis in the current study. An image analysis code was developed which automated the process of observing the centrifugal casting process through an acrylic window on the aft (non-motor) end and using pixel counts calibrated to known o-ring thicknesses to determine solidified distance of wax once per second over a casting time between 10-13 minutes. Once solidification distances were inferred from video footage, data was differentiated to estimate instantaneous solidification rates which revealed that the rate slightly but steadily increased over time for both beeswax and paraffin, though moreso for beeswax.

Coning was observed in both the paraffin and beeswax casted grains, though considerably more with the latter wax. Future work will utilize aluminum as the casting tube material. With its four-order-of-magnitude increase in thermal conductivity as compared to polycarbonate, casting time and coning should be significantly reduced. Furthermore, testing has already begun to evaluate casting tube length and diameter dependence for both waxes.

An upcoming flight onboard a parabolic trajectory microgravity aircraft will complement results from two prior flights on this same vehicle. The next flight will be the first of this research effort involving liquefied paraffin and beeswax for determining rotation rate thresholds in microgravity which sustain reliable annulus formation in form factors identical to those presented in this work.

An upcoming flight on the Blue Origin New Shepard vehicle will provide three minutes of uninterrupted microgravity time to attempt an entire solidification run on paraffin inside of a casting chamber considerably smaller than those used in this study, due to the 2U allowable volume of the entire experiment including heater, camera, and control systems.

Acknowledgments

The authors would like to thank Best Bees and the Urban Bee Lab for providing, free of cost, the base materials for beeswax production and providing guidance during the beeswax refining process and Katlyn Turner for considerable editorial contributions to the text. Miles Lifson, Christine Joseph, Cate Waft, Michael Mazumder, Milo Hooper, and Minsu Jung contributed to earlier portions of the larger research effort which laid a strong foundation for the work described herein.

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