Optical and Thermochemical Analysis for Paraffin and Beeswax Centrifugal Casting

Optical and Thermochemical Analysis for Paraffin and Beeswax Centrifugal Casting

Keith Javier Stober[1], M. Regina Apodaca M.[2], Alana Sánchez[3], Anika Kamath[3], Gabriel Owens-Flores[3], Dinuri Rupasinghe[3], Ana Emilia Hernández Lara[4], Gladys Chepkirui Ngetich[5], and Danielle Wood[6]

Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA

Abstract

Progress on the wax-based centrifugal casting project is presented. A chemical equilibrium solver was used to predict nearly identical but slightly superior performance of beeswax compared to paraffin under identical conditions and in the case where (1) gaseous oxygen and (2) nitrous oxide are employed as oxidizers. An experiment was conducted in the laboratory and onboard a microgravity aircraft flight which leveraged water, 5W-30 motor oil, liquefied paraffin wax at 100 ℃, and beeswax at 100 ℃ as working fluids in geometries on par with small-scale tabletop hybrid rocket fuel grains – 2 in. internal diameter and 10 in. internal length. Sixteen total microgravity parabolas were flown with rotation rates varying from 0 to 800 RPM. Annulus formation was dependent upon viscosity. Oil and paraffin produced annuli in microgravity at 150 RPM and most rotation rates above. Water twice produced annuli in microgravity at 550 and 800 RPM. Beeswax was not rotated in microgravity such that the static geometry of liquefied wax could be studied. Identical tests were conducted for oil and paraffin in the laboratory. Paraffin never achieved annulus when tested up to 800 RPM in the laboratory. Oil achieved annulus at 650 RPM and above.

I. Nomenclature

PCM	=	phase change material
RPM	=	rotations per minute
HTPB	=	hydroxyl-terminated polybutadiene
Isp	=	specific impulse

[1] Research Engineer, Space Enabled Research Group, MIT Media Lab, AIAA Professional Member
[2] Graduate Research Assistant, Space Enabled Research Group, MIT Media Lab, AIAA Student Member
[3] Undergraduate Research Assistant, Space Enabled Research Group, MIT Media Lab
[4] Independent Research Assistant
[5] Postdoctoral Researcher, Space Enabled Research Group, MIT Media Lab, AIAA Professional Member
[6] Assistant Professor of Aeronautics & Astronautics and Media Arts & Sciences, Director, Space Enabled Research Group, MIT Media Lab, AIAA Professional Member

II. Introduction

The Space Enabled Research Group at MIT is conducting a multiyear research effort to better understand the technical and logistical challenges posed by the implementation of a wax-based hybrid chemical in-space propulsion system. Paraffin and beeswax are being considered as candidate fuels. Prior work by the authors introduced the concept of reusing phase change material (PCM) from satellite thermal insulation as fuel for deorbit, reviewed current and prior work in the area of beeswax as a hybrid rocket fuel, detailed the steps of the image processing routine for solidification rate characterization, and presented results from two microgravity aircraft flights alongside tabletop testing in the laboratory.[1-4]

The overarching effort includes imagery analysis conducted on paraffin and beeswax centrifugal casting tests on progressively higher-fidelity experimental platforms within transparent hardware which aids in optical investigations. Such platforms include a laboratory optical table and vacuum chamber, a parabolic trajectory microgravity aircraft (three flights to date; most recent May 2021), the Blue Origin New Shepard suborbital launch vehicle (three flights scheduled for 2021/2022), and the Destiny laboratory module of the International Space Station (ISS; launch scheduled for 2021/2022). Each of these platforms allows for testing in a new environment or longer-duration microgravity. The parabolic aircraft flights allow 20 parabolas of 20-25 seconds each, the New Shepard flight 3 minutes, and the ISS flight one month of continuous microgravity time for testing. Atmospheric vs. vacuum experiments allow for isolation of convective and radiative effects on cooling and solidification of the wax, while 1g vs. microgravity experiments allow for evaluation of the role of buoyancy in the convective cooling process.

The work described herein complements contemporaneous work conducted within the research group and with collaborators in the area of computational modeling of the flow physics associated with the centrifugal casting process and in the area of simulating the heat transfer problem within a 3U CubeSat on orbit which considers the effect of various orbital parameters on melting and solidification.[5,6]

Results presented in this paper include thermochemical calculations of the performance of paraffin and beeswax vs. HTPB as well as the presentation of in-house rotation rate and heating control systems employed simultaneously in centrifugal casting studies. Furthermore, the imagery analysis provides time to liquid annulus formation under various conditions, particularly as a function of rotation rate.

III. Technical Approach

The campaign to characterize the centrifugal casting process of paraffin and beeswax has ground as well as flight project components. The ground components consist of tabletop laboratory testing as well as vacuum chamber testing, while the flight components consist of parabolic trajectory aircraft, suborbital, and orbital testing. In addition to experimental work related to casting, a chemical equilibrium solver is used to compare predicted performance of paraffin, beeswax, and hydroxyl-terminated polybutadiene (HTPB) hybrid rocket fuels under identical conditions which warrants continued study of beeswax as a candidate *green* hybrid rocket fuel.

A. Ground-Based Projects

1. Table Top Solidification Testing

An image of the primary ground-based and microgravity experimental setup is shown in Figure 1. A detailed description of the experimental setup is provided by Stober et al.[2] The primary components are a casting tube which is generally transparent polycarbonate (but sometimes aluminum for higher conductivity testing), an Arduino-based DC motor control system which interfaces the 12V, 5A DC motor, and a frame which provides structural support. For studies involving melted wax, a heating system is employed at the surface of the casting tube. The ground-based setup houses dedicated ground-based investigations as well as test runs in preparations for flight testing (e.g., design and development of in-situ heating, motor control investigations, optimal geometry evaluation, imagery analysis routine development, etc.). For ground-based studies, length, diameter, thickness, and material properties of the casting tube are studied alongside the primary independent variable: rotation rate.

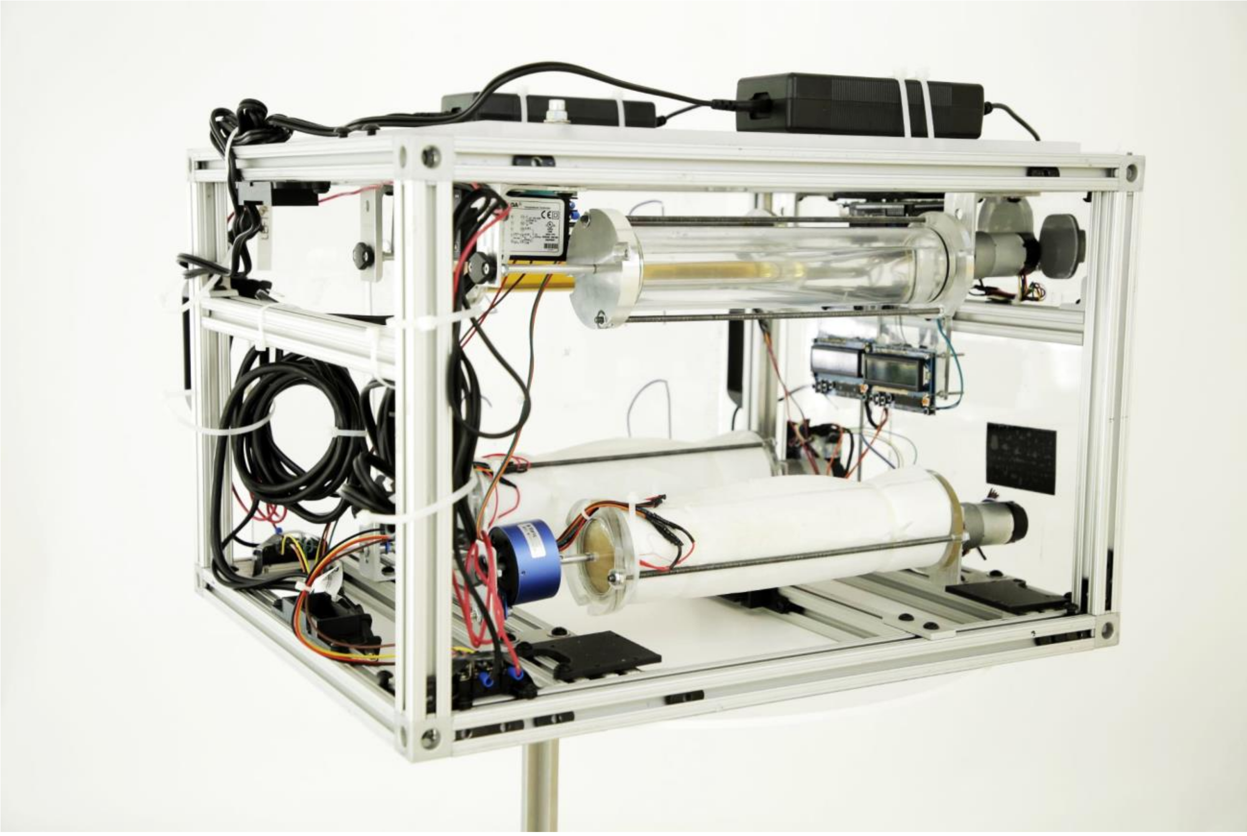

Fig. 1 Tabletop laboratory and microgravity experimental setup for centrifugal casting of wax. The working fluids are housed in cylinders arranged in a 2x2 configuration, with white insulation seen on the bottom two cylinders housing the melted waxes.

During ground testing, an imagery analysis routine was developed and perfected which automated the process of determining instantaneous and average solidification rates of paraffin and beeswax. The details of the imagery analysis routine were previously presented by Stober et al.[2] The current study expands these techniques for use on additional ground tests as well as all flight tests.

2. Motor and Heating Control System Upgrades

The experimental electrical system consisted of two main subsystems: the motor control and the heating control. Both subsystems were built entirely from off-the-shelf components. The electrical system was powered via two power strips that were connected to wall power sockets that were provided by the flight operators. For safety reasons, the two power strips were used as emergency stop buttons and powered heaters separately from the rest of the components.

The heating system consisted of a single high-power heating pad and a thermocouple for each of the wax casting tubes that were then connected through the slip rings to a Omega CN740 thermo controller. The selected thermo controller is a commercially available PID controller that would read out the temperature of the tube in real time as well as the predetermined desired temperature.

On the other hand, the motor control system consisted of an Arduino Mega as the microcontroller, a Pololu Metal Gearmotor 37Dx65L mm 12V with 64 CPR Encoder, a dial pad and an LCD screen. The casting experiment had two of these motor setups, one for both of the top cylinders, and another for the paraffin wax cylinder. An additional Arduino dual motor shield was needed for the controller that connected to the top two cylinders. The dial pad allowed the flyers to control the start and end of a run, as well as the applied RPM. The LCD displayed the run number and the desired RPM to help keep track of the runs.

For the purpose of this experiment, the optical system was treated separately since both the cameras and any additional lighting were fully battery operated.

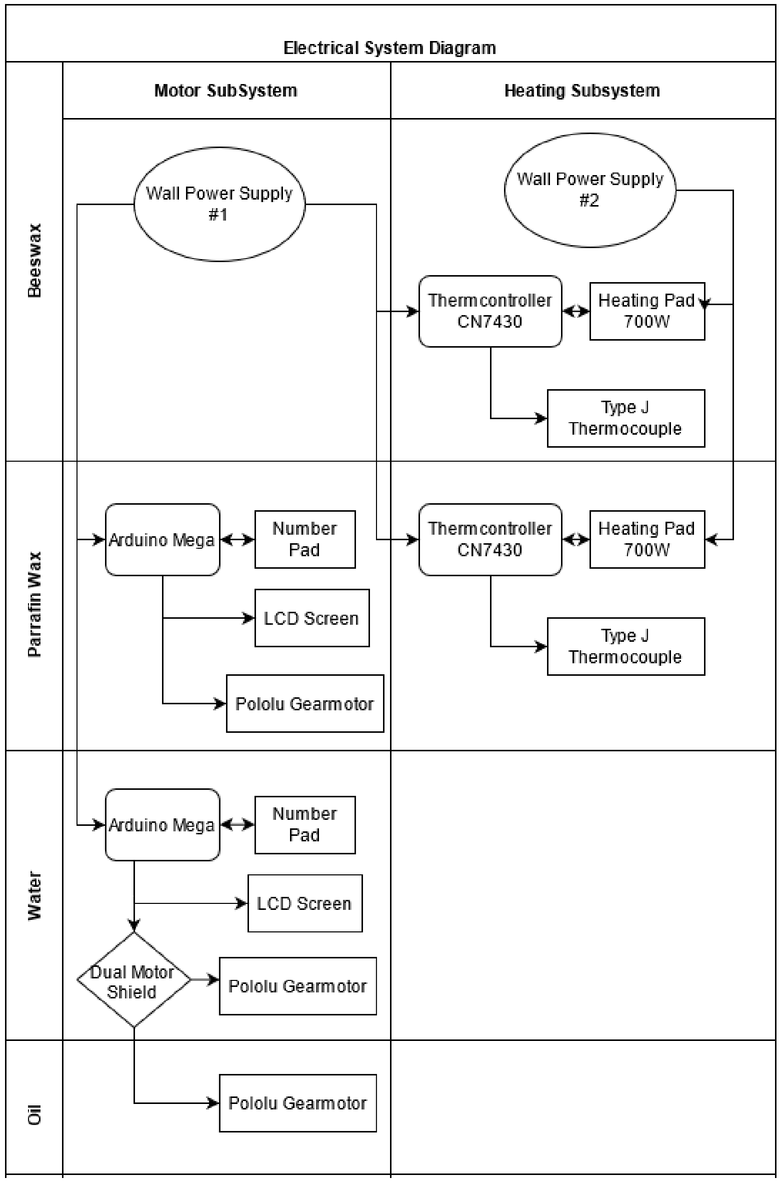

Fig. 2 Electrical diagram of motor and heating control system used to accurately and reliably rotate casting tubes from 0-800 RPM and heat paraffin and beeswax tubes to between 25-100 °C.

B. Flight Projects

1. Parabolic Trajectory Microgravity Aircraft

Short-term microgravity tests can be conducted on the Zero-G Corporation's parabolic trajectory microgravity aircraft, a modified Boeing 727 which flies at least 20 parabolas yielding minimum 20 seconds of microgravity per parabola as well as the option for Lunar or Martian gravity parabolas. These short duration flights are insufficient to conduct solidification testing but have proven invaluable in the pursuit of annulus formation data as a function of rotation rate. That is, these flights only allow for fluid mechanics studies but not multiple phase change studies. The first two flights were flown previously using water and oil as the working fluid, respectively, while a third flight was conducted in May 2021 and comprised four side-by-side centrifuges containing water, oil, paraffin, and beeswax. The experimental setup for the first two flights is seen in Figure 3 and a description of the results were previously presented by Stober et al.[1-4] A solid model of the experimental setup for the most recent flight is seen in Figure 4.

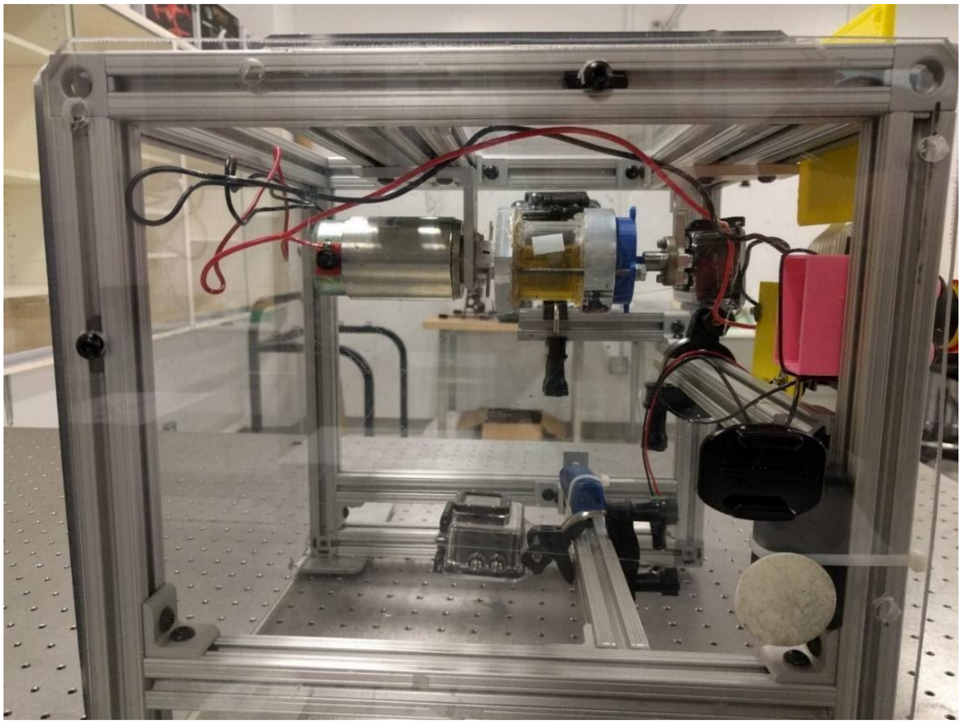

Fig. 3 Microgravity experiment flown on the second of three parabolic trajectory aircraft flights nearly identical to that flown on the first flight. The DC motor and casting tube are at top left and top center, respectively.

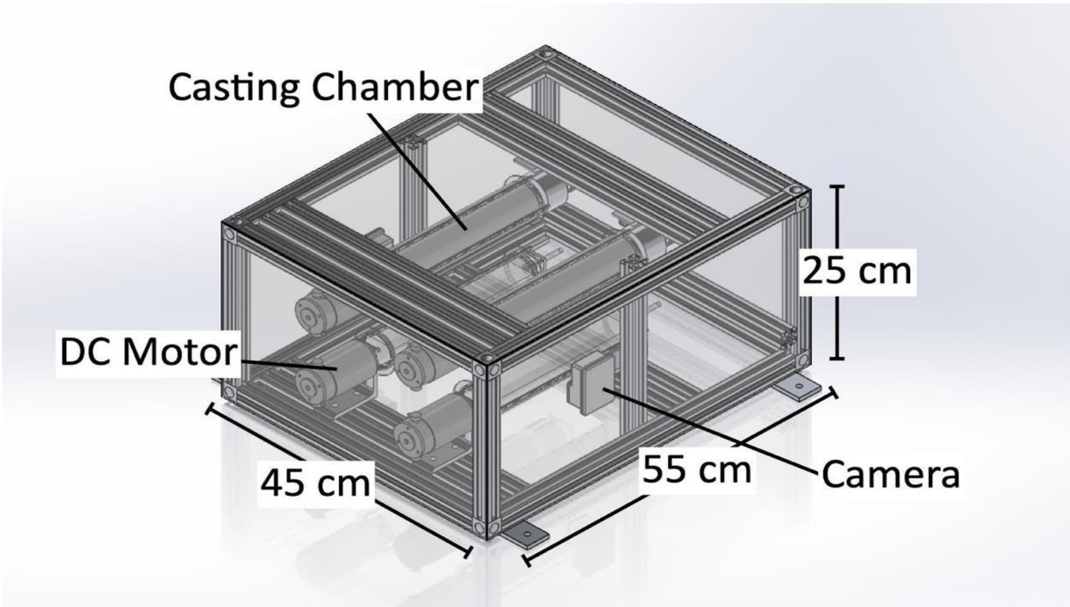

Fig. 4 Solid model of microgravity experiment for the third parabolic trajectory aircraft flight including four parallel centrifuges holding paraffin, beeswax, oil, and water.

2. Suborbital Space Flight

Three upcoming flights are scheduled onboard the Blue Origin New Shepard suborbital flight vehicle. On the first flight, the centrifugal casting experiment is constrained to a 2U volume which allows for one working fluid (paraffin) and a miniaturized casting tube. A notional representation of the experiment for the first flight is shown in Figure 5. The second suborbital flight experiment will occupy an entire single payload locker and include paraffin and beeswax centrifuges as well as possible additional experiments contributed by collaborators. The single payload locker provides approximately 25 times more volume and 100 times more power than the 2U, enabling significantly larger centrifuges.[7] In each of these flights, the first several minutes will be spent melting the wax with the goal of a completely liquid working fluid prior to the onset of microgravity. Microgravity durations of three minutes for each flight will allow for partial solidification of the wax, as observed by an onboard camera. The imagery analysis routine will be conducted on the retrieved inflight video in order to assess the impact of buoyancy on convective cooling of the centrifuge.

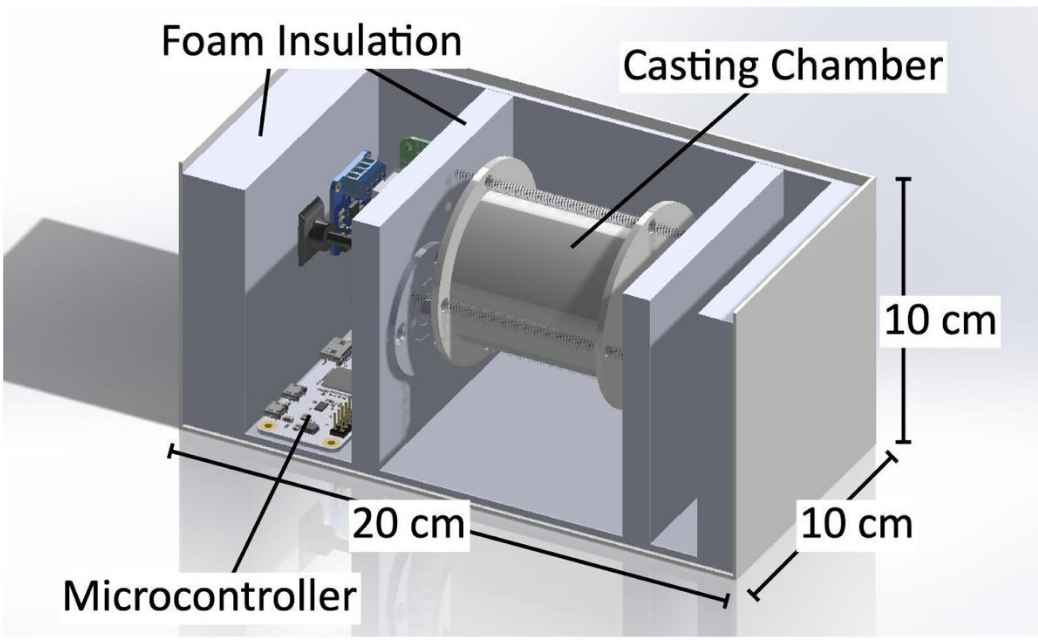

Fig. 5 Notional experimental setup for first suborbital spaceflight constrained to 2U volume.

3. Orbital Space Flight

One upcoming flight is scheduled to the Destiny laboratory module of the ISS with a mission duration of one month. Such an extended microgravity duration will allow for numerous cycles of wax melting and resolidification in order to explore the influence of rotation rate upon solidification rate in the microgravity environment. The automated experiment will be able to operate 24/7 over the entire month onboard the Station with data downlinked continually. The space allotment is roughly 10U, which will allow for at least one centrifuge. A notional model of the ISS wax casting experiment is shown in Figure 6.

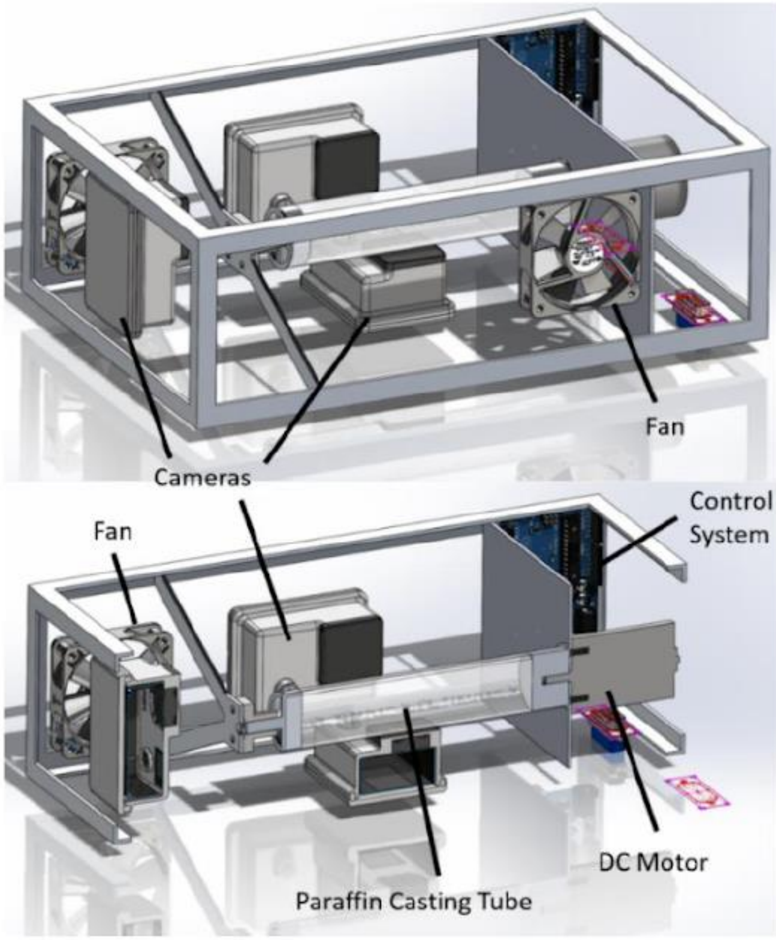

Fig. 6 Notional experimental setup for casting experiment onboard 30-day mission to ISS.

4. Thermochemical Analysis

The continued focus on beeswax as a candidate hybrid rocket fuel warranted a deeper analysis of beeswax performance with gaseous oxygen and nitrous oxide oxidizers compared to paraffin and HTPB. A NASA thermochemical equilibrium solver, Chemical Equilibrium with Applications, was used to predict various measures of rocket performance.[8] Specifically, characteristic velocity, combustion chamber temperatures, specific impulse, and other critical dependent variables were evaluated. Table 1 shows inputs to the thermochemical calculation.

Table 1: Fuel characteristics serving as inputs to the thermochemical calculator.

Fuel	Chemical Formula	Specific Enthalpy (kcal/mol)
Beeswax	$C_{46}H_{92}O$	-197.9[9]
Paraffin	$C_{32}H_{66}$	-231.3
HTPB (butadiene)	C_4H_6	7.648[10]

IV. Results

A. Thermochemical Analysis

The results of the thermochemical calculations are shown in Figures 8-12. These results indicate that beeswax, paraffin, and HTPB exhibit very similar performance which corroborates that the renewability and cost advantages of beeswax warrant its further study as a high-performing hybrid rocket fuel.

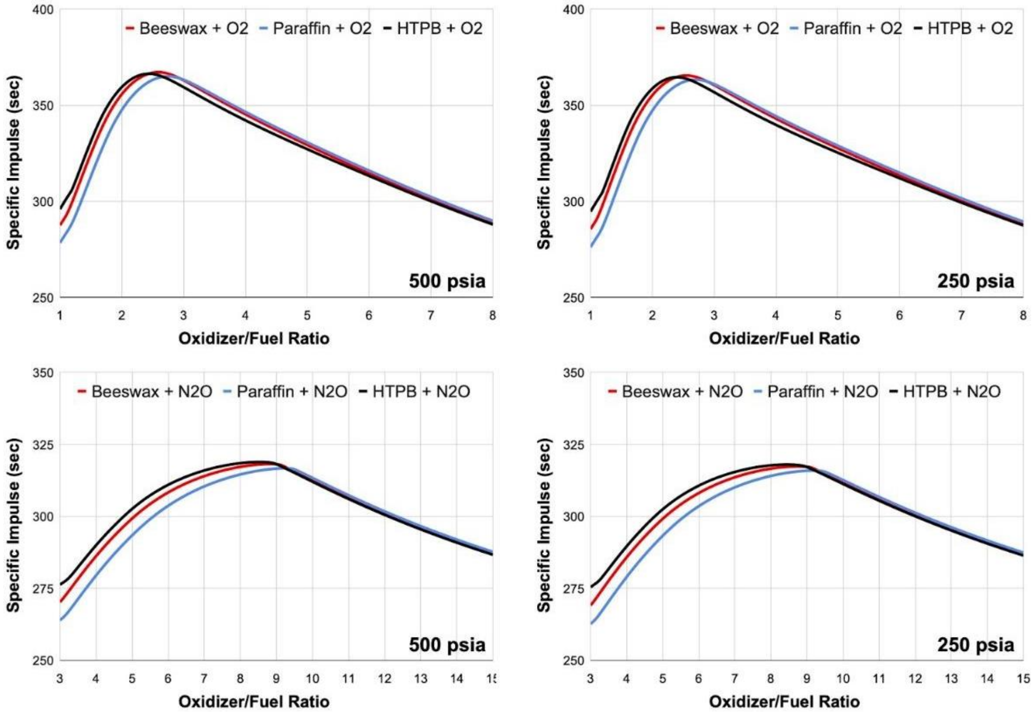

Fig. 8 Comparison of the vacuum specific impulse against the oxidizer-to-fuel ratio for beeswax, paraffin, and HTPB with O2 and N2O at 250 and 500 psia with a nozzle area ratio of 50.

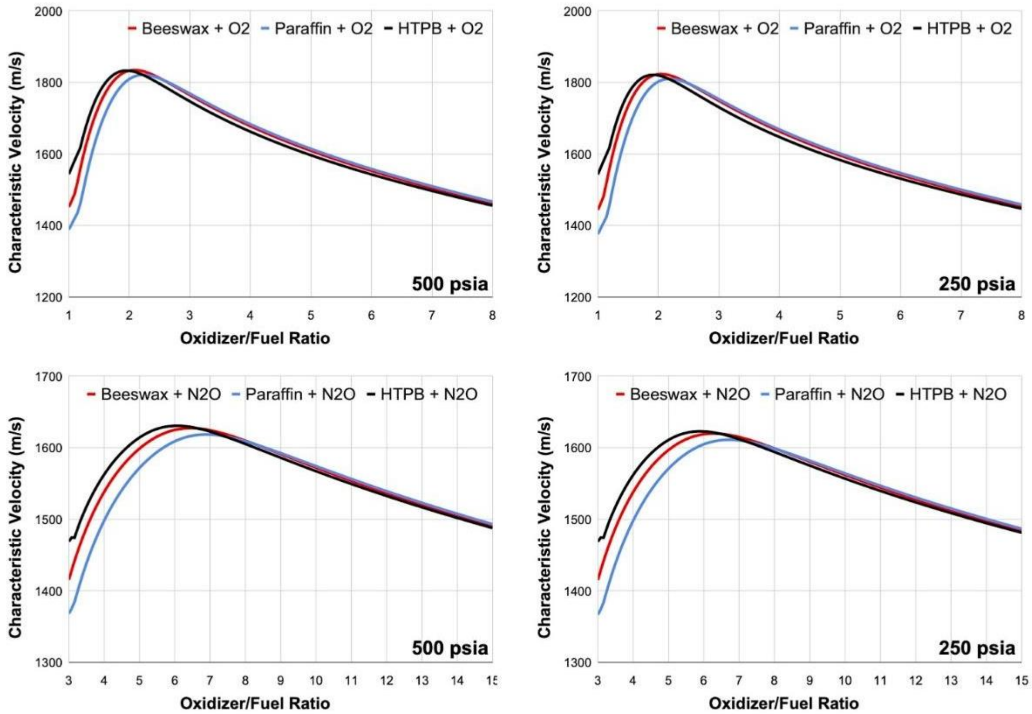

Fig. 9 Comparison of the characteristic velocity against the oxidizer-to-fuel ratio for beeswax, paraffin, and HTPB with O2 and N2O at 250 and 500 psia with a nozzle area ratio of 50.

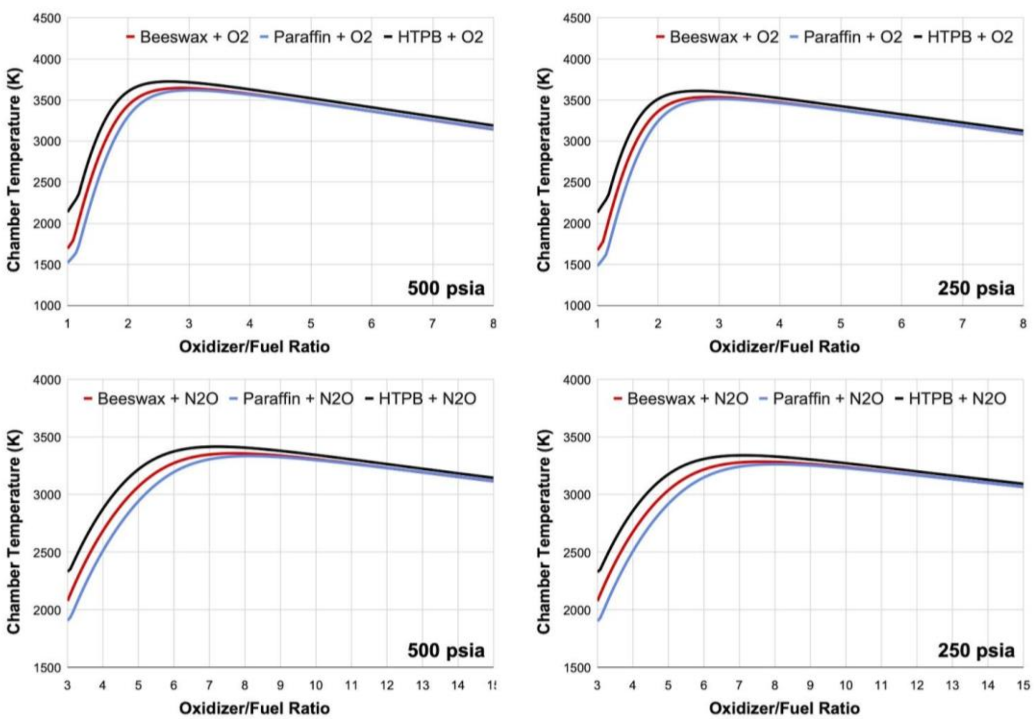

Fig. 10 Comparison of the combustion chamber temperature against the oxidizer-to-fuel ratio for beeswax, paraffin, and HTPB with O2 and N2O at 250 and 500 psia with a nozzle area ratio of 50.

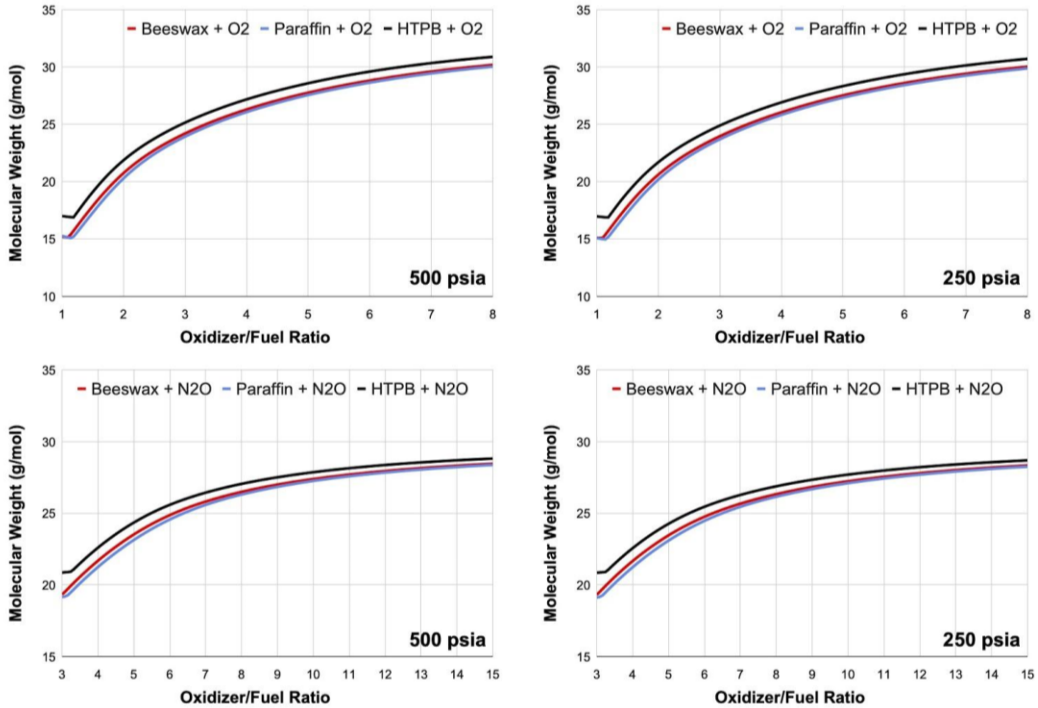

Fig. 11 Comparison of the molecular weight of combustion products against the oxidizer-to-fuel ratio for beeswax, paraffin, and HTPB with O2 and N2O at 250 and 500 psia with a nozzle area ratio of 50.

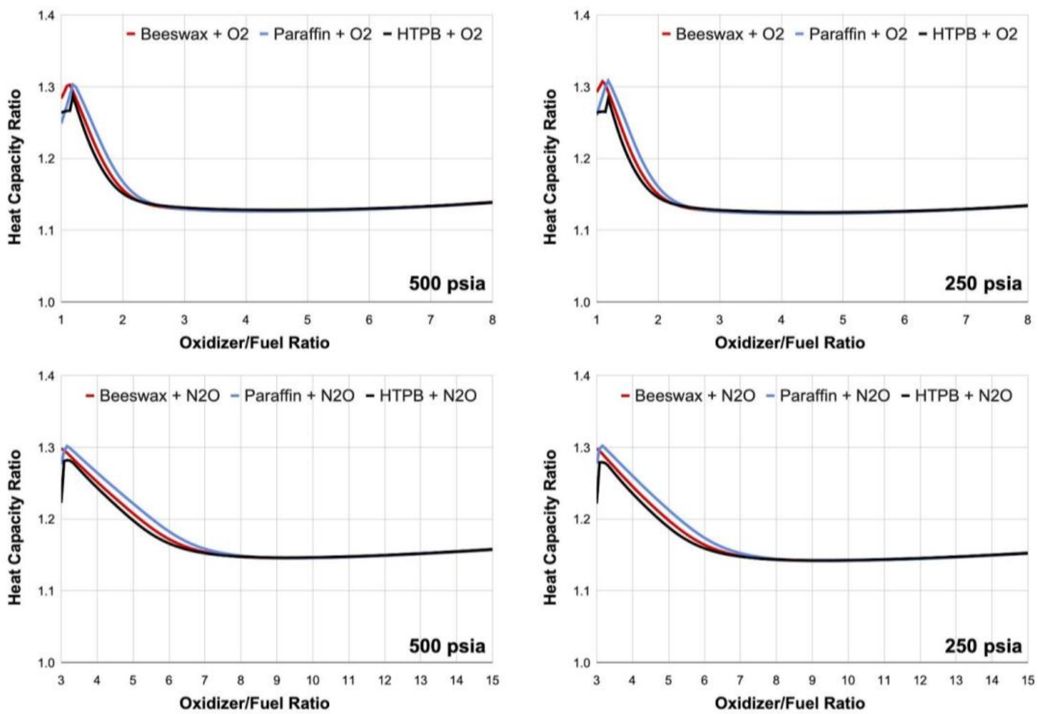

Fig. 12 Comparison of the ratio of specific heats within the combustion chamber against the oxidizer-to-fuel ratio for beeswax, paraffin, and HTPB with O2 and N2O at 250 and 500 psia with a nozzle area ratio of 50.

C. Microgravity Results

All else equal, viscosity of the working fluid determined the ease with which it formed an annular shape under the influence of rotation. Therefore, oil was most susceptible to annulus formation followed by paraffin and water. Figures 13-14 show the progression of fluid geometry of oil in a case that reached and did not reach annulus, 100 RPM and 450 RPM, respectively. Figures 15-16 show the progression of fluid geometry of liquefied paraffin wax at 100 ℃ in a case that reached and did not reach annulus, 100 and 450 RPM, respectively. Figures 17-18 show the progression of fluid geometry of water in a case that reached and did not reach annulus, 650 and 800 RPM, respectively. Figures 19-20 illustrate the anticipated inverse relationship between time to achieve annulus and rotation rate observed in both oil and liquefied paraffin wax at 100 ℃ in microgravity. Static beeswax in microgravity did not demonstrate notable, repeatable changes in fluid geometry when subjected to microgravity. It was previously hypothesized that liquefied beeswax may tend towards the edges of the casting tube due to surface tension effects, thereby forming something resembling an annulus, but no evidence of this was found during any of the microgravity parabolas.

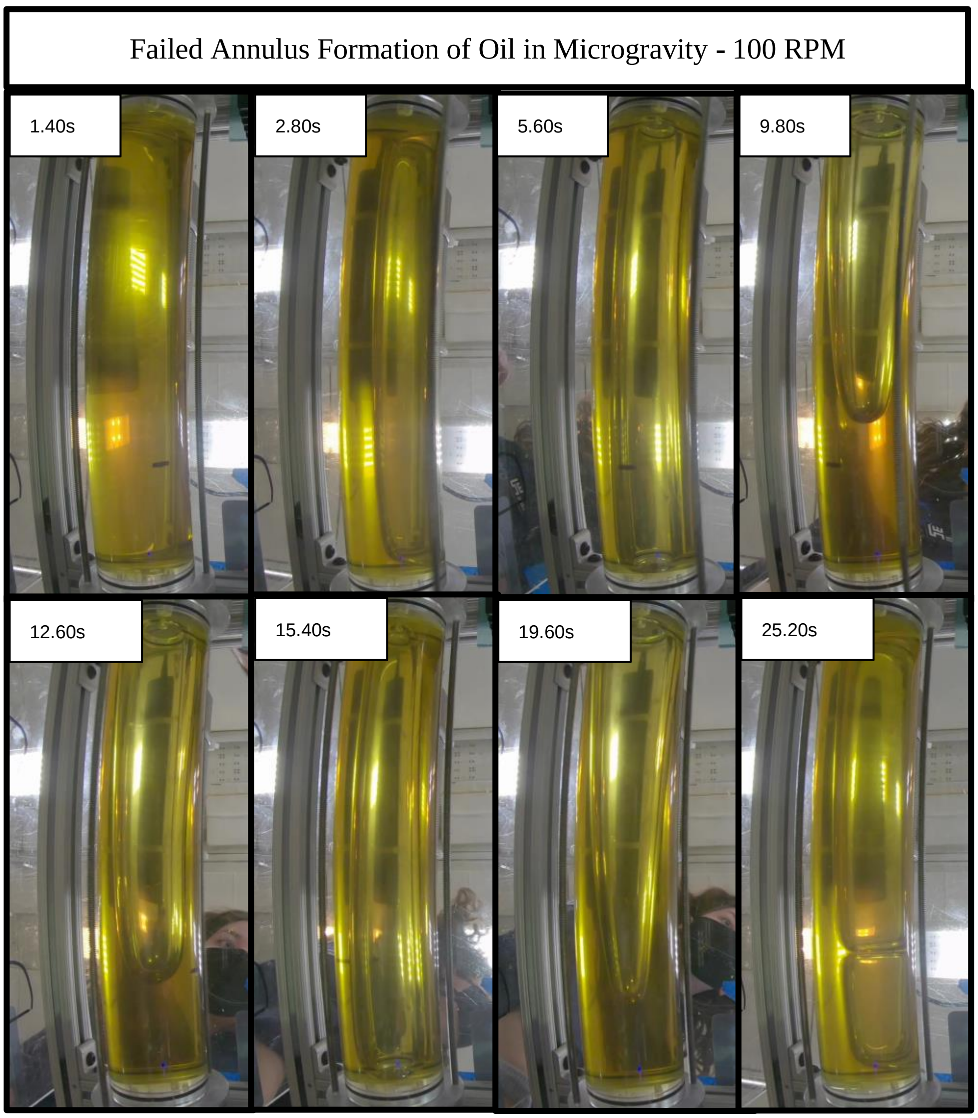

Fig. 13 Progression of annulus formation of oil at 100 RPM in microgravity which fails to achieve annulus and makes closest approach at 15 s into the microgravity parabola.

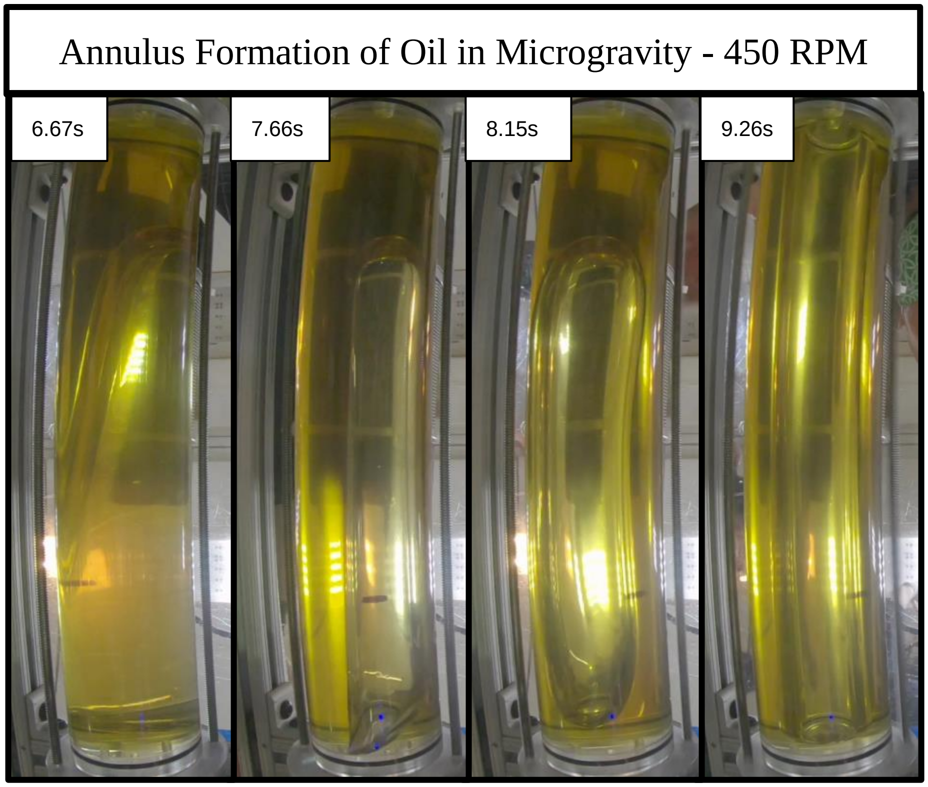

Fig. 14 Progression of annulus formation of oil at 450 RPM in microgravity which achieves annulus 9 s into the microgravity parabola.

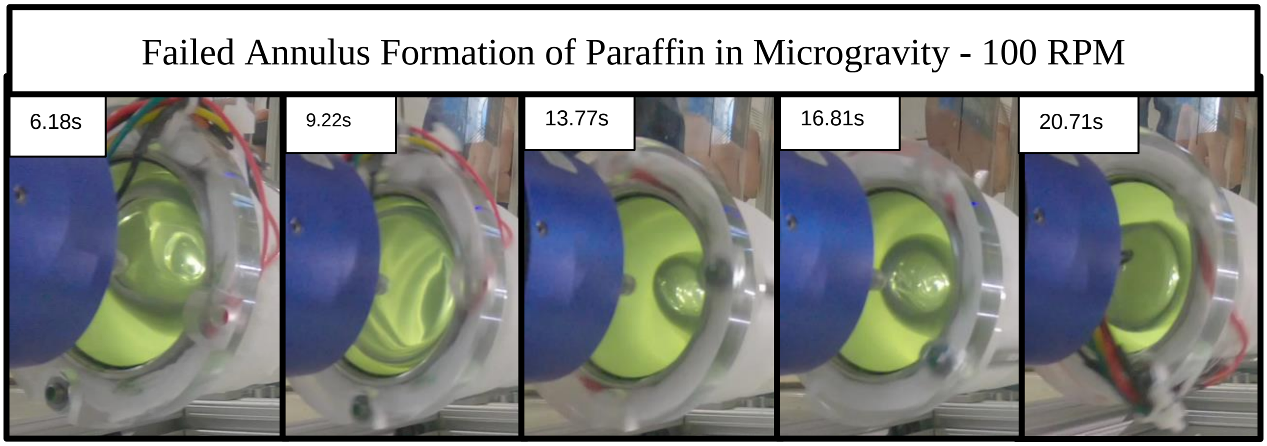

Fig. 15 Progression of annulus formation of liquefied paraffin wax at 100 °C at 100 RPM in microgravity which fails to achieve annulus and makes closest approach 20 s into the microgravity parabola.

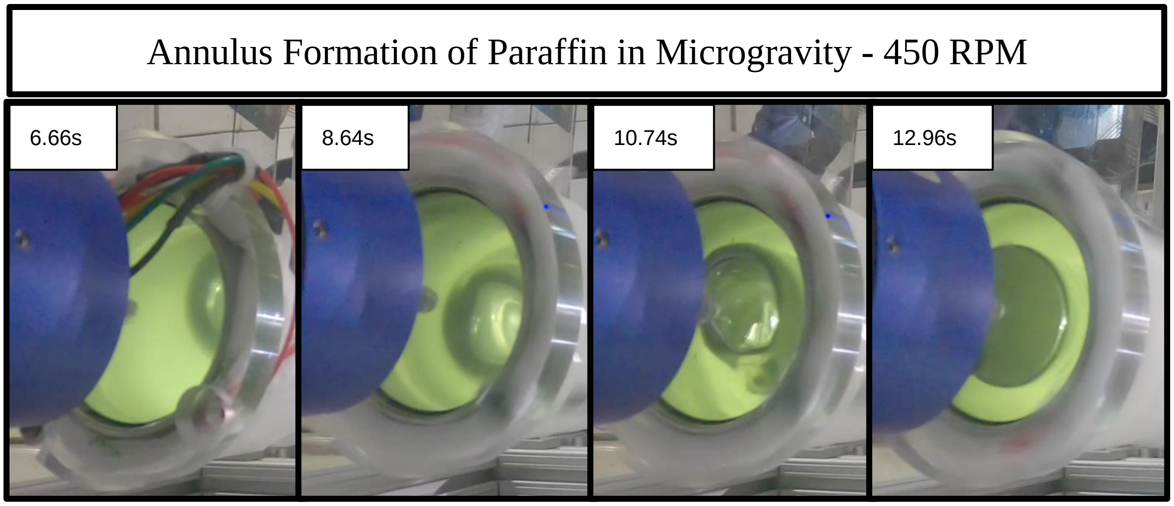

Fig. 16 Progression of annulus formation of liquefied paraffin wax at 100 °C at 450 RPM in microgravity which achieves annulus 13 s into the microgravity parabola.

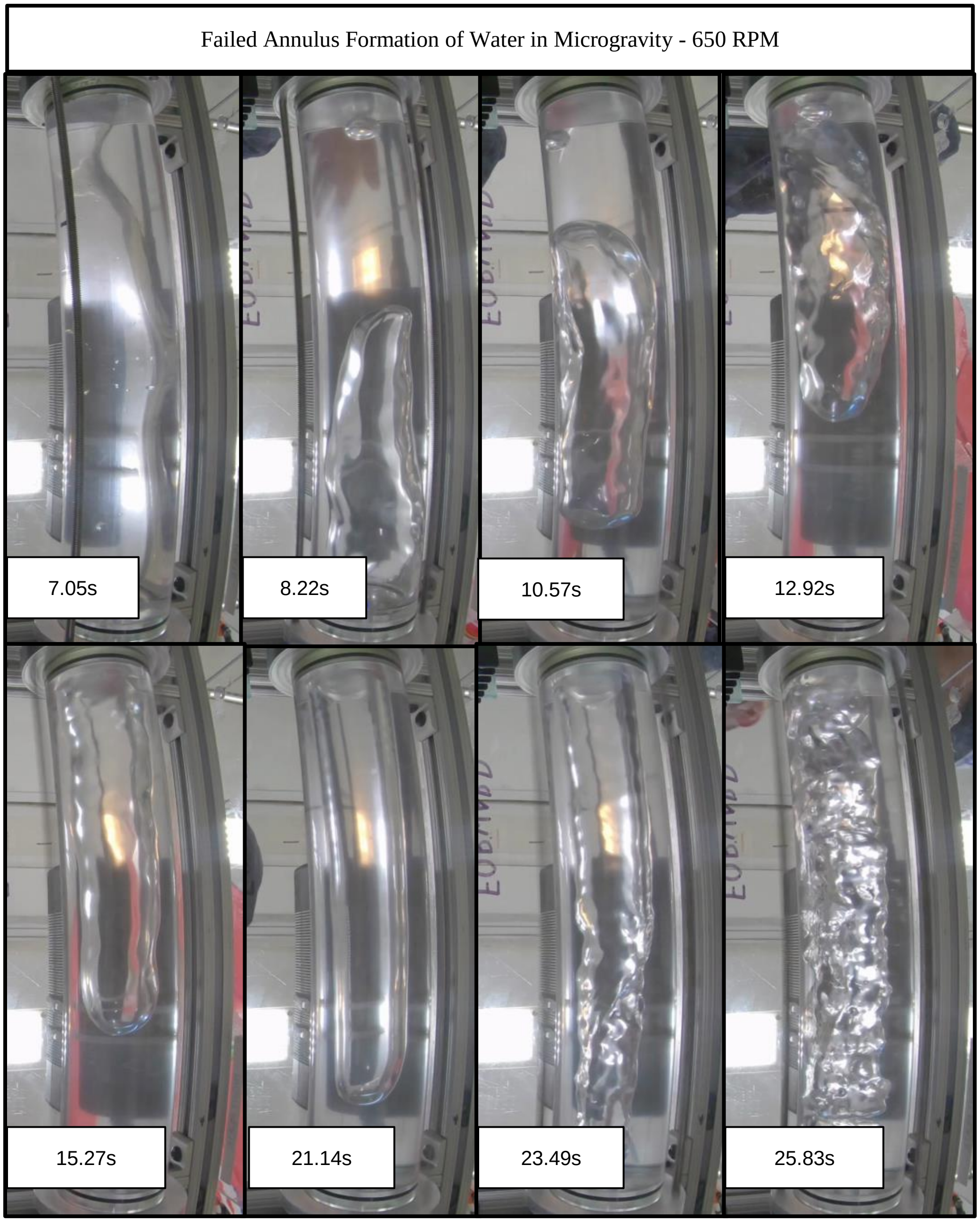

Fig. 17 Progression of annulus formation of water at 650 RPM in microgravity which fails to achieve annulus and makes closest approach 21 s into the microgravity parabola.

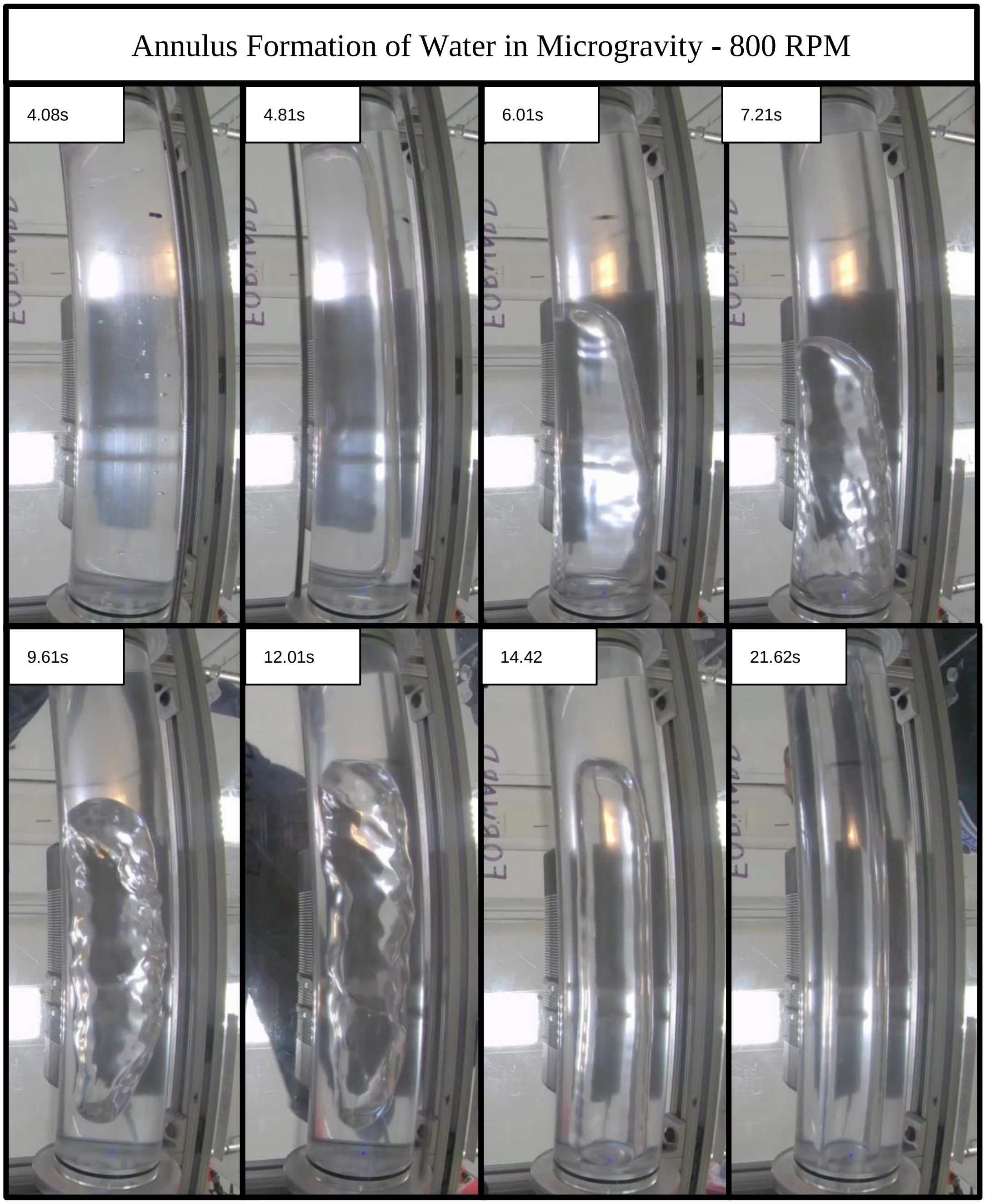

Fig. 18 Progression of annulus formation of water at 800 RPM in microgravity which achieves annulus 22 s into the microgravity parabola.

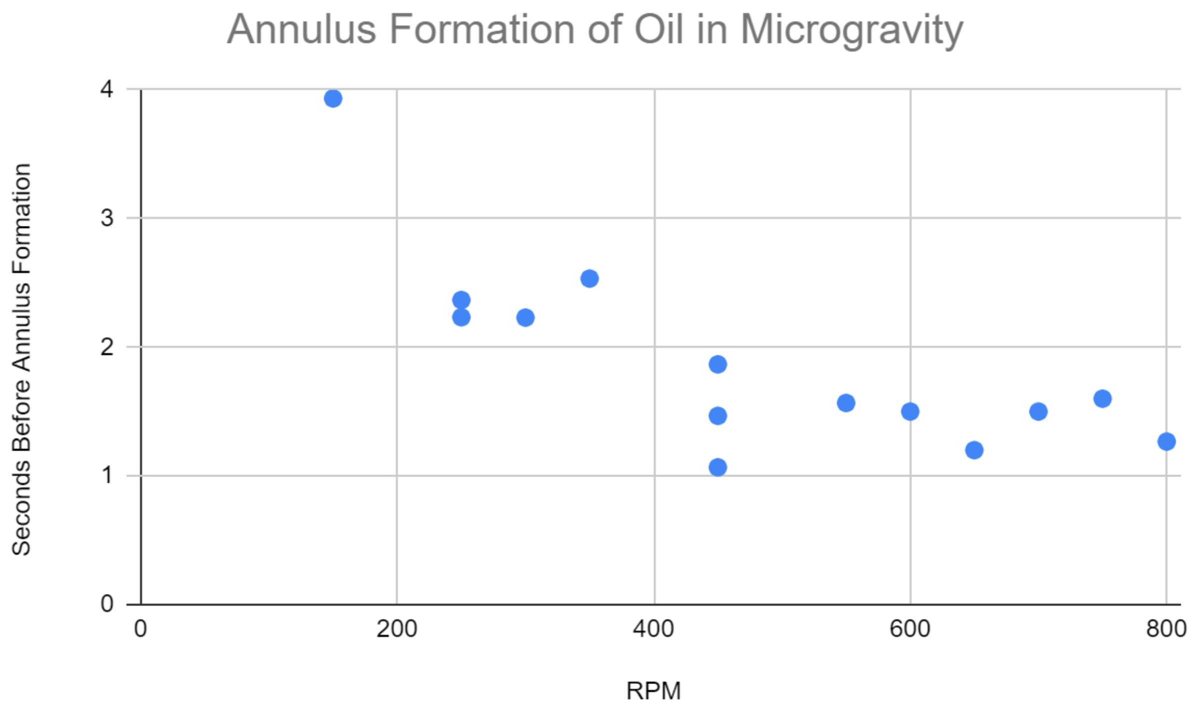

Fig. 19 An inverse relationship between time to annulus formation and rotation rate was observed for the case of oil in microgravity.

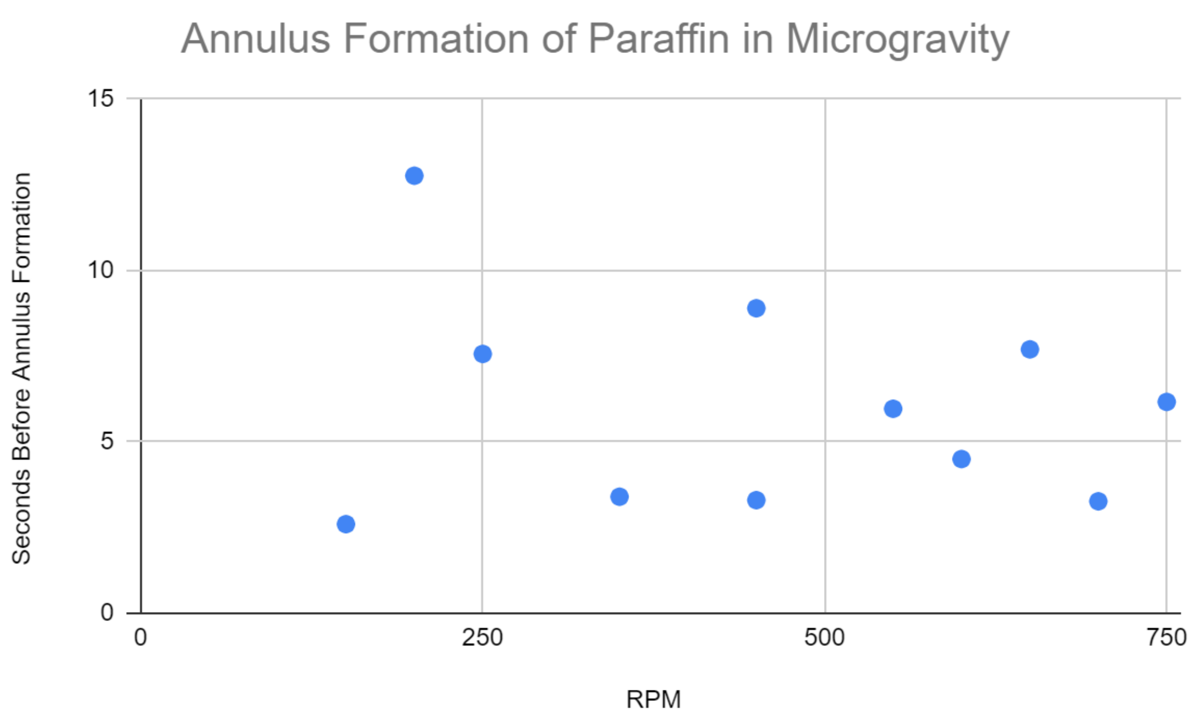

Fig. 20 An inverse relationship between time to annulus formation and rotation rate was observed for the case of liquefied paraffin wax at 100 °C in microgravity.

D. Laboratory Results

Experimental testing was conducted for oil and liquefied paraffin at 100 °C in the laboratory at conditions identical to those in microgravity except in the 1g environment. The goal of these tests was to understand the degree to which microgravity lowers the rotation rate threshold to achieve annulus in the rotating liquid. Under these conditions, liquefied paraffin wax never achieved annulus despite rotation rates up to 800 RPM. Oil achieved annulus at rotation rates of 650 RPM and above. Figures 21-22 shows the progression of fluid geometry of oil in a case that reached and did not reach annulus, 100 and 650 RPM, respectively. Figure 23 shows the progression of fluid geometry of liquefied paraffin wax in a case that did not reach annulus, 50 RPM. Figure 24 illustrates the inverse relationship between time to annulus and rotation rate observed in oil in the laboratory. Comparing this figure to Figure 19 shows the significant shift in rotation rate threshold to produce an annulus in oil.

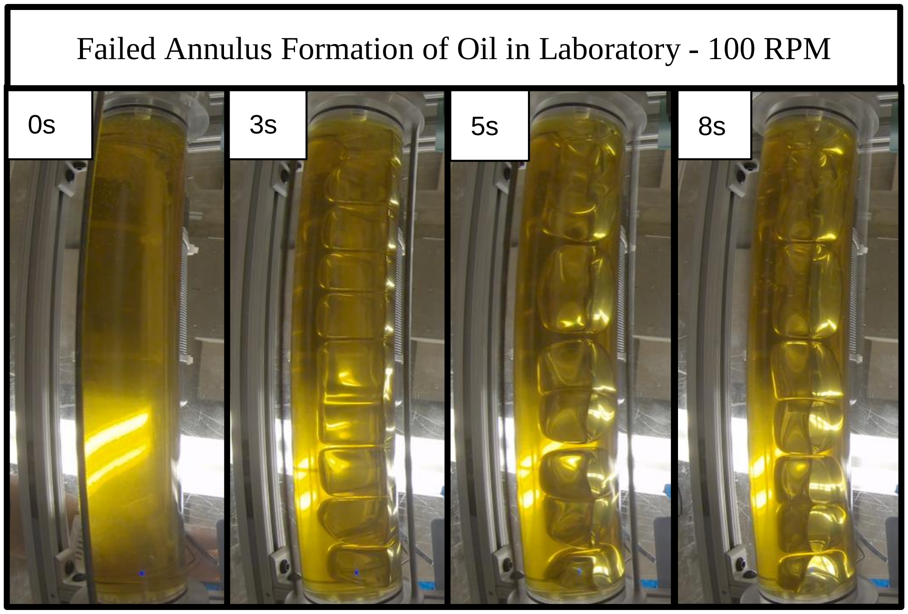

Fig. 21 Progression of annulus formation of oil at 100 RPM in the laboratory which fails to achieve annulus and reaches quasi-steady state 8 s after the onset of rotation.

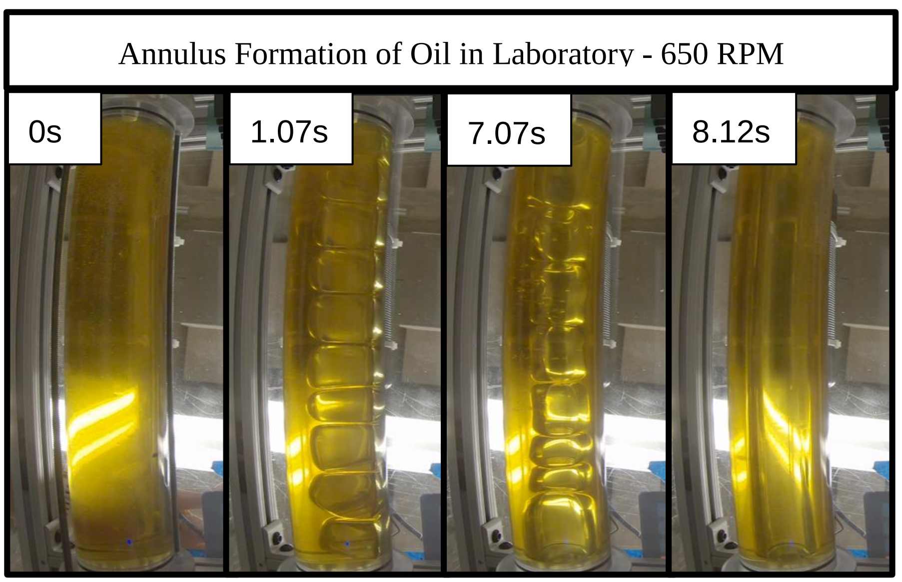

Fig. 22 Progression of annulus formation of oil at 650 RPM in the laboratory which achieves annulus 8 s after the onset of rotation.

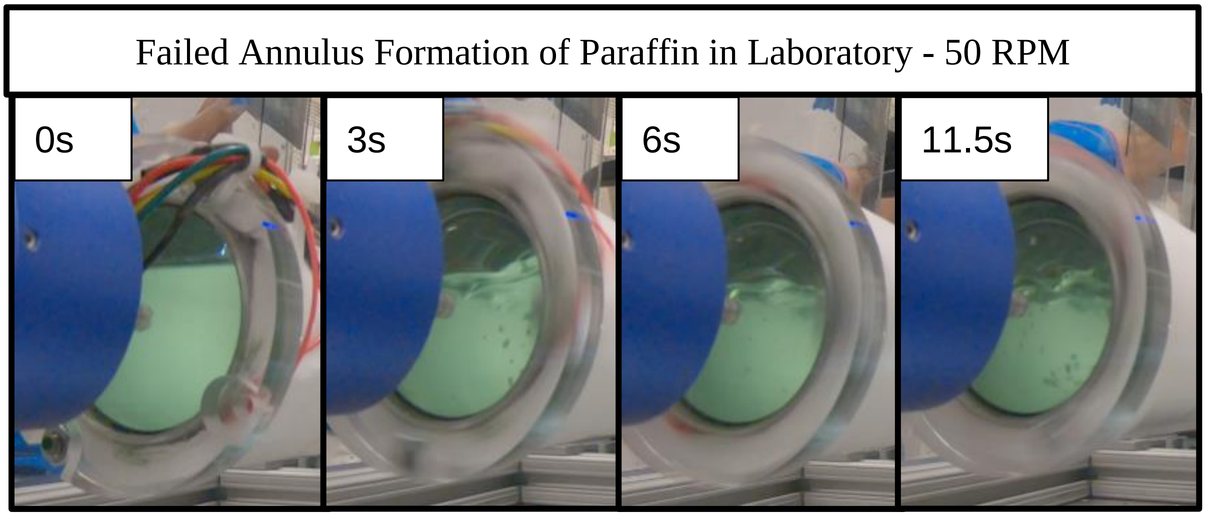

Fig. 23 Progression of annulus formation of liquefied paraffin wax at 100 °C at 50 RPM in the laboratory which fails to achieve annulus and reaches quasi-steady state 12 s after the onset of rotation.

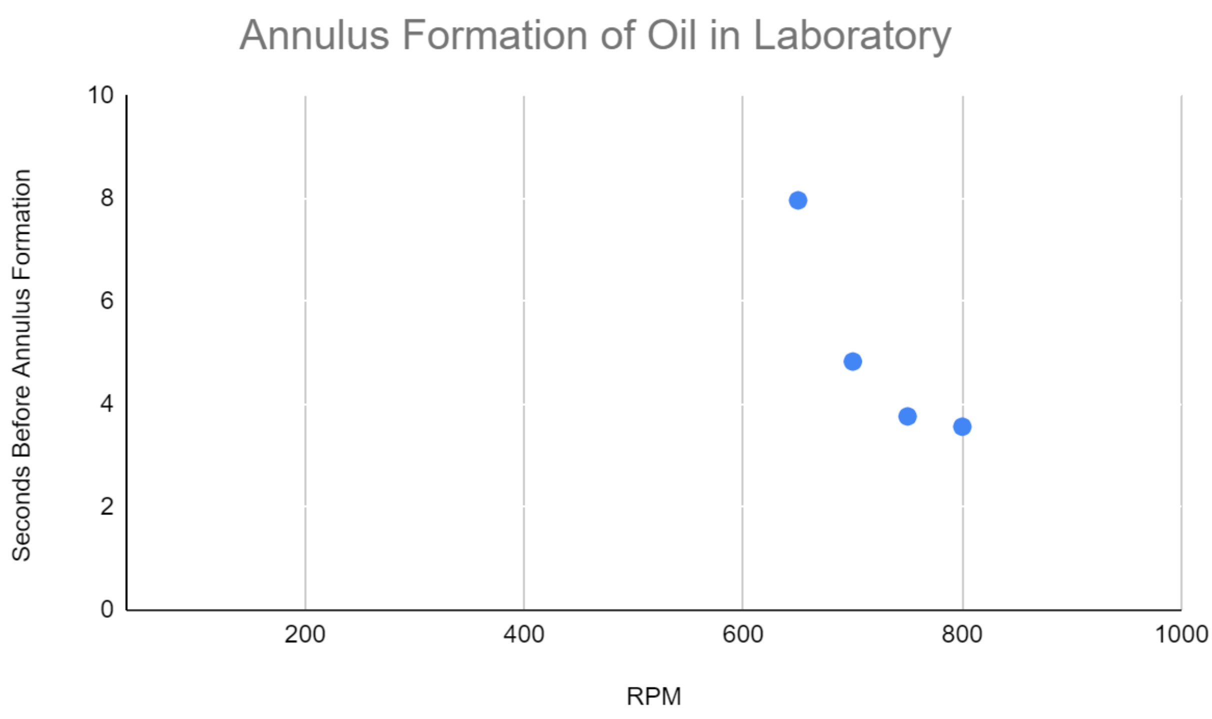

Fig. 24 An inverse relationship between time to annulus formation and rotation rate was observed for the case of oil in the laboratory which was significantly shifted to the right compared to the microgravity case.

V. Summary and Future Work

Thermochemical calculations were undertaken to explore predicted performance comparisons between beeswax, paraffin, and HTPB which show similar performance for each with beeswax being slightly superior to paraffin under identical conditions when considering specific impulse and characteristic velocity. Of note is the slight shift in oxidizer-to-fuel ratio to the left for peak performance of beeswax vs. paraffin, which may be attributable to the atom of oxygen present in the beeswax molecule. This shift to the left could lead to reduced oxidizer tank volume and mass when employing beeswax compared to the case of paraffin. These results motivate continued study of beeswax as a candidate green hybrid rocket fuel. Side-by-side hot fire studies are needed to experimentally validate the results presented here.

The laboratory and microgravity centrifugal casting tests of oil, water, liquefied paraffin, and liquefied beeswax successfully demonstrated the rotation rate reduction for achieving annulus in microgravity compared to laboratory conditions. The case of oil demonstrated this most clearly, with the threshold for annulus production reducing from 650 to 150 RPM when moving from laboratory to microgravity. The rotation rate threshold for annulus production for the case of liquefied wax in the laboratory could not be determined at these geometries due to rotation rate limitations of the selected motor, but was in excess of 800 RPM, and reduced to 150 RPM when moving to the microgravity environment. These results suggest that centrifugal casting of paraffin wax onboard a satellite is not likely to be ruled out based on rotation rate concerns alone. As a follow on to the static liquefied beeswax test, the next Blue Origin New Shepard flight will employ a static tube of liquefied paraffin in order to see what geometries are produced during the three-minute duration microgravity portion of the flight.

Upcoming experimental tests include laboratory tests where casting tube diameter and length are varied, as well as paraffin and beeswax temperature, as the viscosity of these liquefied waxes tends towards that of oil as they approach solidification temperatures. Furthermore, a higher rotation rate motor will be employed to obtain data up to 1500 RPM where stable annuli are expected for liquefied paraffin wax, based on prior work.[4] Finally, the upcoming 30-day mission to the ISS Destiny Module will allow for solidification rate vs. rotation rate characterization in microgravity to complement an identical test campaign in the laboratory and better understand whether particular rotation rates lead to desirable mechanical properties of the fuel or significantly reduced solidification times which are preferable to simplify logistics should this technology be implemented on an orbital mission.

VI. References

[1]Stober, K.J., Wanyiri, J., Sanchez, A., Hooper, M., Mazumder, M., Jiwani, S., Waft, C., Lifson, M., Joseph, C., and Wood, D., "An Investigation of the Centrifugal Casting of Paraffin Wax in the Laboratory and in Microgravity," AIAA 2019-4012, AIAA Propulsion and Energy Forum, Indianapolis, IN, 19-22 August 2019.

[2]Stober, K.J., Wanyiri, J., Sanchez, A., Jiwani, S., Hooper, M., Mazumder, M., Lifson, M., Joseph, C., and Wood, D., "An Investigation of the Laboratory-Based and Microgravity Centrifugal Casting of Paraffin Wax," IAC-19-A2.3.1.52725, 70th International Astronautical Congress, Washington, D.C., 21-25 October 2019.

[3]Stober, K.J., Sanchez, A., Wanyiri, J., Jiwani, S., and Wood, D., "Centrifugal Casting of Paraffin and Beeswax for Hybrid Rockets," AIAA 2020-3736, AIAA Propulsion and Energy Forum, 24-26 August 2020.

[4]Stober, K.J., Sanchez, A., Apodaca M., M.R., Ngetich, G., Erkel, D., Wanyiri, J., and Wood, D., "Leveraging Microgravity to Investigate Earth- and Space-Based Centrifugal Casting of Wax," IAC-20-A2.3.4.58780, 71st International Astronautical Congress, CyberSpace Edition, 12-14 October 2020.

[5]Ngetich, G.C., Stober, K.J., and Wood, D., "Numerical Simulation of Centrifugal Casting of Paraffin Wax: Part 1 - Influence of Rotational Speed, Fluid Viscosity, Tube Diameter and Volume Fill Fraction," submitted, AIAA Propulsion and Energy Forum, Denver, CO, 9-11 August 2021.

[6]Leuteri Costanzo, D., Stober, K.J., Wood, D., and Colombo, C., "Modelling and Simulation of In-Orbit Centrifugal Casting of a Paraffin Wax Grain Inside a 3U CubeSat," submitted, AIAA Propulsion and Energy Forum, Denver, CO, 9-11 August 2021.

[7]Blue Origin, "New Shepard Payloads," https://www.blueorigin.com/new-shepard/new-shepard-payloads/, 2020, accessed February 2021.

[8]Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications," NASA Reference Publication 1311 (1996).

[9]Putnam, S.G., “Investigation of Non-Conventional Bio-Derived Fuels for Hybrid Rocket Motors,” Graduate Thesis University of Tennessee, Knoxville, 2007.

[10]Shafeeuulla Khan, M.A., Abhijit, D., Javaid, A., and Sikder, A.K., “Calculation of Enthalpies of Formation and Band Gaps of Polymeric Binders.” *RSC Adv.* 4, no. 62 (2014): 32840–46. https://doi.org/10.1039/c4ra02847c.