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Development of a Micro-Scale Plasma Arc Gasification System for Long Duration Space Mission Waste Processing

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The reuse of discarded materials on a long duration or planetary mission is a critical component in reducing overall mission mass and creating useful commodities like fuel, water and repurposed construction materials. Plasma arc gasification converts the majority of organic waste into a synthesis gas (syngas), consisting primarily of hydrogen, carbon monoxide and carbon dioxide, and inorganic waste into a solid slag material that can be used as a construction aggregate. Plasma arc gasification had not been previously investigated for space applications, and could potentially provide a cleaner product than other waste processing methods. The NASA Space Technology Mission Directorate Center Innovation Fund at Kennedy Space Center (KSC) funded a one year investigation for the development of a micro-scale plasma arc gasification system for waste repurposing on long duration space missions. The micro-scale plasma arc gasification system was designed, fabricated, and tested at KSC with a commercial plasma torch. This paper discusses the project development and results regarding the use of plasma at low power and the challenges of plasma arc gasification for small scale waste conversion.

Nomenclature

AC = alternating current
Cp = specific heat, J kg^{-1} K^{-1}
HFWS = high fidelity waste simulant
$\dot{m}$ = mass flow rate, kg s^{-1}
MPG = micro-scale plasma arc gasification
Q = heat flow, Watts
RF = radio freqwuency
SLPM = standard liters per minute
T = temperature, K
TtG = Trash-to-Gas

I. Introduction

As humans explore beyond low Earth orbit, a sustainable presence in transit and on extraterrestrial bodies is necessary, which includes waste conversion technologies. Space logistical waste conversion has become an area of technology development for human spaceflight missions.[1–4] Technologies that reduce the volume of logistical waste, as well as generate commodities from mission waste, are a sustainable and necessary means of maintaining

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human presence on any extraterrestrial land mass, cislunar station, or long-duration mission. Since it currently costs approximately 10,000 U.S. Dollars per 0.5 kg of payload launched into orbit [5], the fuel gained from trash conversion can provide a significant cost savings.

A. Trash to Gas

Trash to Gas (TtG) was one of four projects under the NASA "Logistics and Reduction Repurposing" Advanced Exploration Systems project from 2012 to 2014. The TtG effort investigated six technologies for waste-to-fuel production. KSC initially investigated pyrolysis, incineration/gasification, and later steam reforming.[6–8] The result of the TtG project determined that a steam reforming reactor was the most effective for power, mass, and conversion purposes.[9] The steam reformer required 2 kW of power for operation, which was calculated from a theoretical value of the energy necessary to convert water to steam. Plasma arc gasification was not a waste degradation technology investigated during TtG. The TtG steam reformer results concluded that up to 1,540 kg of methane or 270 kg of water can be produced over a yearlong mission from the waste generated by a crew of four. Venting of trash via TtG would reduce total logistics and propellant system mass for a Mars mission (a lighter vehicle would mean less propellant needed to decelerate on arrival to Mars). However, using the products from waste conversion would be more ideal (rather than venting) due to propellant mass savings when launched from Earth. In 2015, the KSC Center Innovation Fund funded the "Micro-scale Plasma Arc Gasification for Waste Treatment and Energy Production" (MPG) project to investigate the use of plasma arc gasification to convert high fidelity waste simulant (HFWS) on long duration space missions into useful commodities.

On a human spaceflight mission, waste is stored in cargo transfer bags until it is jettisoned off from a disposal vehicle on the International Space Station and burned up in Earth's atmosphere. Small waste bags of HFWS were prepared using a composition of long duration mission waste that was described in previous work.[9,10] The HFWS consisted primarily of urine brine, clothing, food, fecal, logistical waste (packaging, duct tape, gloves) and hygiene waste (shampoo, toothpaste, wipes).The HFWS was formulated in 100 g batches, shredded, placed in 0.5 L plastic bags, compressed, and stored in the waste feed system before MPG or TtG system operation.

B. Plasma Arc Gasification

State-of-the-art plasma arc gasification is typically a high-power direct current (DC) system that often uses air for the plasma carrier gas because it is abundant and low-cost. Literature has reported on theoretical modeling and some lab scale and pilot plant designs for DC, radio frequency (RF), and microwave discharge methods.[11–20] These studies show that introducing steam or oxygen rich feedstocks enabled higher throughput of hydrogen and synthesis gas (syngas) production. The power scale (megawatts) of large waste processing was not a reasonable expectation for long duration space mission waste conversion systems. MPG evolved to attempt use the theoretical high throughput and "clean" syngas output that plasma arc gasification claims to offer, while attempting to reduce the plasma arc torch power requirement to less than 2 kW, using an alternating current (AC) system.

Argon (Ar) was a good carrier gas to initiate a plasma arc because of its low ionization potential, and required the lowest voltage to obtain AC plasma arc ignition. The low power requirement was key for novelty of the system because low power consumption will be crucial for long-duration travel and a design constraint onboard spacecraft and in habitation systems. Power initiated through the neutral carrier gas from the power supply causes the electrical breakdown processes, which causes the plasma arc to form. According to Paschen's law for breakdown voltage of various gases, the voltage breakdown versus pressure reaches a minimum (1 Torr-cm). If the pressure and distance are decreased too much, there is not enough gas to sustain a plasma plume. As pressure and distance from the arc discharge is increased above the minimum, the breakdown voltage increases. This is because the secondary electrons from the cathode are colliding too often, the electrons traveling to the anode are also colliding too often, and more power is needed in order to build up enough energy to ionize the neutral carrier gas molecule. The theory of Townsend discharge was used to estimate the breakdown, or sparking potential, of a gas between two electrodes. Paschen's law provides the empirical formula that relates the theory of Townsend discharge as a function of pressure.[21]

II. Experimental Set Up

A. Process Design

The MPG reactor size was designed based on the description of the plasma torch characteristics from the plasma arc torch supplier, Plasma Energy Applied Technology (PEAT) International. PEAT provided a preliminary calculation of reactor volume based on processing 0.1 kg of trash per minute at temperatures of 900 °C or higher, and also recommended sub atmospheric operating pressure for this specific AC plasma torch. A custom built transformer to power the AC plasma torch was manufactured by Pacific Transformer Corporation based on the description of the torch from PEAT. The AC plasma torch was described to have a maximum current of 350 mA for a 6500 V torch ignition, followed by a high-feedback, arc-driver-type design with a flux-limited transformer controlled by power. Every 8 ms, a restrike of the arc would send the voltage sway from 6500 to 100 V. The torch was also described as needing up to 21 A during continuous operation and lower voltage as arc ignition was achieved.

The high level flow diagram of the MPG system is shown in Figure 1. The waste entered the reactor vessel zone via a feed system and transferred into the reactor where it came in contact with the plasma plume. The product was then sent into a post reactor gas processing system. The post reactor gas processing system consisted of a heat exchanger, water collection vessel, chemical scrubber, and vacuum pump. A ‘BOC Edwards’ Model XDS 5c oil-free scroll pump was used as a vacuum source to pump the reactor system down to sub atmospheric pressure during operation.

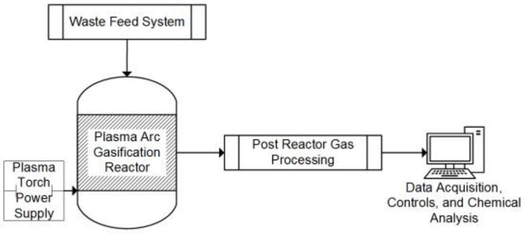

Figure 1. MPG high-level schematic.

B. Reactor System

The MPG system model is displayed in Figure 2. A feed system was attached to the reactor vessel that also housed a manual gate valve that was initially shut to prevent trash from prematurely filling the reactor vessel. The waste feed pipe volume (before the gate valve) was 1.5 L and stored 600 g of HFWS, loosely packed. This was six times the volume capacity of the previously designed TtG gasification and steam-reforming reactor. During operation, the gate valve was opened and an actuator (Tolomatic 610 mm stroke) on a movable track pushed the waste through a side-loading port inlet. The waste entered the reactor at a 90-degree angle from the top side of the reactor. The reactor vessel (316/316L stainless steel) had a flange adapter that was angled into the reactor and the plasma torch was bolted to the adapter. Tubes were located throughout the external body of the reactor to accommodate two pressure transducers and three thermocouple sensor ports. Product gas left the vessel via a 50.8 mm diameter pipe, where it was then fed into the post reactor gas processing system. Inconel baffles, were placed inside the reactor to provide a ‘tortuous path’ of gas exit in order to increase the residence time.

Figure 2. MPG model of feed system, reactor body, and reactor body with labels.

Portions of the internal body of the reactor base and reactor lid were lined with a 50 mm thick refractory concrete (Ultra-Green 57A from Refractories-West, Incorporated) barrier to provide thermal uniformity in the reaction zone. A weight-saving method of thermal protection for the reactor was also demonstrated using a row of alumina-enhanced thermal barrier (AETB-8) ceramic tiles in the upper portion of the reactor body (Figure 3, top). AETB-8 was a lightweight ceramic tile insulation that was used in NASA programs such as the X-38 Crew Return Vehicle. A thin layer of Saffil alumina fiber blanket was also placed between tile and refractory joints as a cushion. A Grafoil GHR flexible graphite gasket was added to the top flange of the lid of the reactor vessel, and the reactor was purged with gaseous nitrogen for 24 hours before use. A video camera was installed on a port through the reactor lid to allow top-view observation of the plasma arc during operation. Figure 3 (bottom) is an image of the entire MPG system set up in a laboratory fume hood. Thermocouples, pressure transducers, and mass flow controllers were wired into a National Instruments ‘cDAQ USB’ chassis system with five input/output modules for data collection. The analog input and output signals were processed by original software written in LabVIEW 2014.

C. Plasma Arc Torch and Power Supply

The plasma arc torch is displayed in Figure 4. The torch body had a water-cooled casing and could be operated using a variety of carrier gases. Two sintered copper-iron electrodes were used for long duration durability. The plasma torch was powered by the custom built transformer, and used as the power-limiting supply to the plasma arc torch.

Multiple transformer designs were evaluated in this work. The first transformer was capable of delivering 2.2 kVA (kVA = 1000 volt amps) across a voltage range of 6500 to 800 VAC. A second transformer was designed to draw less primary current. This transformer had an unvarnished shunt stack. The shunt stack was constructed of thin sheets of iron-silicon steel, and the height and width of the stack were adjusted during experimentation.

Electrical isolation of the torch body from the grounded reactor was confirmed using a Hipotronics Model HD115 AC/DC high-potential test set. A Synergy data acquisition system (Hi-Techniques Incorporated) was used in conjunction with a resistor network in an attempt to record the voltage output of the transformer during torch operation at a rate of 200,000 samples per second. Voltage, primary input current, and secondary output current (input to the plasma torch) during torch operation were recorded at 100,000 readings per second with a 'LDS NICOLET Vision XP' data acquisition system instrument. Current draw from the torch was measured using a Fluke 337 clamp-meter.

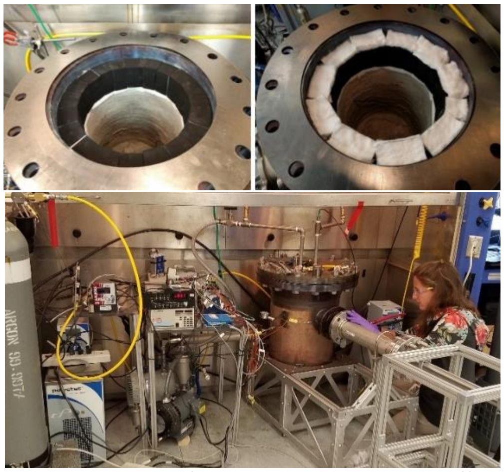

Figure 3. Top: Refractory, AETB-8 tiles and Saffil layers inside reactor. Bottom: MPG system in the laboratory hood.

Figure 4. Plasma arc torch housing. Left: Torch side videw, Middle: Torch plume exit view, Right: Electrode.

D. Experimental Plan

Plasma arc torch performance is affected by variables including power supply, plasma carrier gas (density), carrier gas flow rate, pressure, electrodes, and temperature. Sufficient energy is necessary for plasma to be formed from the carrier gas, and the energy must be continuous so that the plasma was not extinguished. In this case, the energy forming the plasma was electrical, provided by the step-up transformer power supply. The experimental testing of the torch took place in three phases as described below.

1. *Phase 1: Outdoor Torch Testing with Transformer #1:* Integrated plasma torch and power supply were not completed by PEAT International as originally planned, so testing was performed in an outdoor test cell at KSC to gain familiarity with the torch. Torch performance was tested with Ar carrier gas flow rates from 5 to 75 SLPM, and air flow rates from 11 to 50 SLPM at atmospheric pressure.
2. *Phase 2: Laboratory Torch Testing with Transformer #1:* The torch was installed in the MPG reactor vessel shown in Figure 2, and the system performance was evaluated indoors in a laboratory.
3. *Phase 3: Laboratory Torch Testing with Transformer #2:* Testing continued with the second transformer and shunt stack size variations in the laboratory.

After each flow rate test, the plasma arc source was powered off and electrodes were visually inspected.

E. Thermal Modeling and Energy Estimates

Thermal analysis was conducted using STAR-CCM+ with a conjugate heat transfer approach, along with radiation components, to predict and estimate thermal conditions using the chosen reactor design. The thermal model was simplified from the actual hardware model. A single-phase gas at a specified temperature and flow rate emulated the plasma source conditions. Inside the main reactor body (Figure 5), the steel case walls were lined with a layer of refractory. Gas flow followed the guide of the Inconel baffles to the exit pipe. The open volume within the reactor was considered the fluid domain.

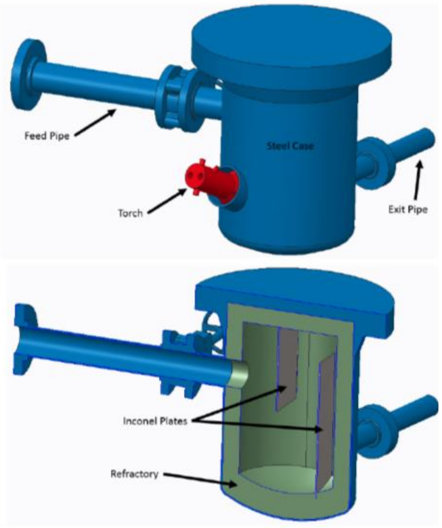

Figure 5. Model overview of outer components (top) and internal geometry (bottom).

There was one inlet at the torch nozzle and one outlet at the end of the exit pipe, and the waste feed pipe was capped at the end.

Turbulence was modeled using realizable k-epsilon two-layer Reynolds-averaged Navier-Stokes equations. At interfaces between the different components, the heat transfer was calculated using physical properties of the materials, and Ar for the carrier gas. The analysis reference pressure was 101.325 kPa. The following boundary conditions were used in the simulation:

1. Inlet: fixed mass flow rate and temperature (5.575e-4 kg s^{-1} and 1,000 ºC).
2. Outlet: fixed pressure (0 Pa gauge).
3. Outer case and pipe: environment conditions (18 ºC ambient temperature and convective heat transfer coefficient of 10 W m^{-2} K^{-1}.
4. Inner core of torch and trash feed pipe end: adiabatic condition.

The density of Ar at 101.325 kPa and 18˚C was calculated by the ideal gas law. The power required to heat up the gas to 1,000 ˚C was calculated by Equation 1. The power needed for ionization of the gas as a basic assumption was 285.5 W.

$$Q = \dot{m} * Cp * \Delta T \tag{1}$$

III. Results and Discussion

A. Phase 1: Outdoor Torch Testing with Transformer #1

The outdoor testing results indicated that 28 SLPM was the optimum Ar carrier gas flow rate for arc ignition and an arc length of approximately 63.5 mm was sustained for nearly 2 minutes. For outdoor testing, the typical behavior of the plasma torch was ignition and arc formation, followed by a large power draw from the transformer. The large current draw from the transformer was a concern, but the transformer current output was observed as 1.0 to 1.4 A into the torch body. The exact cause of the transformer power draw was unknown, and thought to be due to atmospheric pressure operations outdoors. Paschen’s law for Ar indicated that at 0.133 kPa, the plasma can be ignited with the lowest required voltage at 1 cm discharge distance. The thought was that once the torch was operated in the subatmospheric pressure inside of the MPG reactor, the power draw would be lowered and the transformer would work for longer than 2 minutes.

B. Phase 2: Laboratory Torch Testing with Transformer #1

Ar carrier gas flows of 10, 12, 20, 23, 28, and 30 SLPM were tested during indoor laboratory experiments in the MPG reactor. When the torch power supply was turned on, a voltage spike was observed, as high as 4,000 V, and immediately reduced after plasma torch ignition (ignition = when plasma plume was observed on the video camera). The steady state waveform observed was approximately 1200 V peak-peak/300 Vrms and uniform. Current draw was 1.9 A during operation. This translated to an overall power draw of 600 W by the torch.

As the flow rates increased, the size and brightness of the plasma plume increased. There was a minimum and maximum flow at which the torch ignited, and a range of current draw into the torch at 1.0-1.8 A after ignition during all cases. Figure 6 displays imagery of arc ignition inside the MPG reactor vessel. A reactor vessel thermocouple (TC2) can also be seen in the images.

Figure 6. Imagery of varying carrier gas flow rates for Ar plasma arc/plume initiation inside the MPG reactor vessel.

The torch was confirmed to require high voltage and low current for initiation, and then reduced to low current and high voltage during a stabilized arc formation. During nominal operation (stable and visible plasma plume formation) with Transformer #1, the plasma torch required less than 2A of current and less than 1000 V. Overall, less than 2 kW of power was needed for the torch to operate. Results from Phase 2 Laboratory Torch Testing with Transformer #1 showed that the secondary output power to the torch was under the requested 2.5 kVA power design, but the 208 VAC primary input power necessary to maintain the torch arc was significantly higher, measured at over 47 A and approximately 9.8 kVA. The 47 A current would trip the 208 VAC, 30 A laboratory circuit breaker and not allow long-duration torch testing.

C. Phase 3: Laboratory Torch Testing with Transformer #2

When the team faced challenges with Transformer #1, Transformer #2 was received, unvarnished, to modify the transformer shunt stack. Modification of the shunt stack was thought to maintain enough secondary power for a sustained arc, while reducing the transformer primary power for operation in the laboratory. In order to accomplish this, the primary input current needed to be reduced from the 47 A to less than 30 A. Approximately 70 laboratory runs were performed with Transformer #2 to consider all the identified variables, including shunt size, carrier gas flow rate and pressure.

The ideal condition for laboratory operation (208 V, 30 A service) was a shunt size of 71.37 mm thick and 31.75 mm tall. Under these conditions, the transformer provided a range of 1.1 to 2 A into the torch (secondary output) and drew 25 to 30 A from the transformer primary input. The longest continuous torch operation was for 20 minutes with a sustained plasma arc in the empty reactor vessel for an Ar flow rate of 28 SLPM and a presure between 82.7 to 89.6 kPa. The overall pressure observed during all stable plasma plume testing was between 79.2 and 96.5 kPa. The ideal flow rates of the Ar carrier gas were 28 and 29 SLPM. The temperature from the thermocouple 100 mm from the plasma plume did not exceed 68 °C in any tests, including the longest operation of 20 minutes. To reach higher temperatures faster, more power would be needed, or to overcome thermal barriers (such as heating up the internal refractory and the Inconel in the MPG reactor vessel), the plasma torch would need the ability to run longer.

During operation at the successful conditions of the 20 minute operation previously described, the empty reactor had a temperature increase where TC2 increased from 18˚C to 50 °C (Figure 7, A). When shredded cotton cloth was added to the system, the temperature did not achieve the same value, and is shown in Figure 7, B. No visible change was seen in the cloth either after exposure to the plasma plume. A sustained plasma plume was not achieved either for the cloth operation. When shredded paper was inserted from the feed tube to the reactor vessel, TC2 increased from 18 to 66 °C in 2 seconds (Figure 7, C). When the reactor began full of shredded paper in the vessel, temperatures reached 68 °C. The paper lost 0.2 g of mass in a few seconds of plasma exposure and had some visible charring. The plasma torch did not sustain a stable arc for more than 10 minutes with waste additions. Because of the large internal volume of the reactor, more time would be needed with the torch on to heat up the volume of the reactor. The carrier gas is constantly feeding in cooler air at a high flow rate, and so temperature elevation was not observed in these <10 minute runs.

Testing conditions with Transformer #2 did not always produced an arc, and sometimes performance sequence included arc initiation, sputtering, and an extinguished arc, at which time power was shut off. The current on the primary input was controlled with Transformer #2, and machining of the shunts provided higher secondary output. Reducing the width of the shunt stack increased the primary current and secondary transformer output power. The high current draw at the transformer primary input likely occurred due to the magnetic "flux walking" to saturation. When the arc sputtered or became unstable, high power conditions were needed to re-ignite the torch. Because the transformer did not have enough time to recover (flux saturation), the flux density appeared to "choke" the transformer. Without control, an infinite amount of power may have been requested by the torch, as seen in the high current draw. In this situation, the shunt could have acted as a relief, but the dynamic operation of the torch did not allow the shunt to have enough recovery time for the shunt gap needed for the flux lines. This specific MPG plasma torch was a nonlinear power load. When the power transformer is connected to a complex load, like the MPG torch, the large changes in load impedance

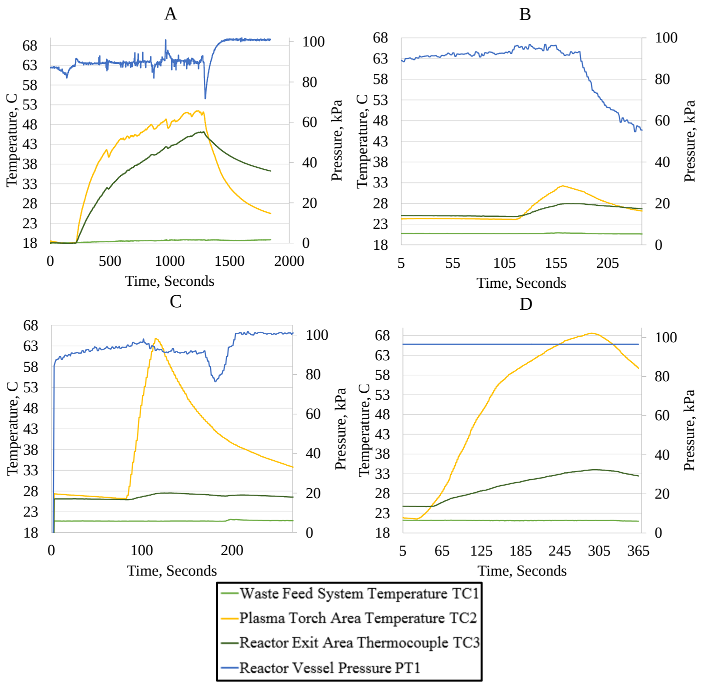

Figure 7. Results from Phase 3 Laboratory Torch Testing with Transformer #2 A) 20-minute torch run with 28 SLPM Ar in the empty MPG reactor; B) single cotton washcloth fed via actuator with 28 SLPM Ar; C) paper fed via actuator with 28 SLPM Ar; D) paper preloaded into reactor with 29 SLPM Ar.

cause undesired primary and secondary power requirements. The transformer had challenges adapting to the load, and the transformer did not reach equilibrium.

Traditionally, power transformer design is been based on sinusoidal voltage and current waveforms operating at low frequencies. The shape of the measured transformer voltage and current waveforms indicated that the torch had significant inductance and capacitance reactive components to its load characteristics. Additional circuitry could be used to correct the power factor to make it seem much more like a resistive load to the transformer, which would then allow for stable operation at lower required transformer power. Some of the test runs showed that the right combination of plasma torch primary and secondary power (ideal shunt stack width and height), carrier gas flow rate, and system pressure might create a stable plasma torch arc suitable for long-duration MPG system testing. When a consistent plasma arc was sustained, the transformer's primary current was observed to decrease to a level significantly below the 30 A required for long-duration laboratory testing. It was also observed that when the torch arc was sputtering (igniting erratically, going out and then reigniting), the transformer's primary current rose significantly. Exceeding the laboratory's 30 A current limit forced early termination of the torch testing.

D. Thermal Modeling

The highest temperature of the solid region was located downstream of the torch where the jet impinged onto the refractory surface. The steel cup behind the refractory reached a maximum temperature of approximately 114 ºC. The relative temperature ranges between the fluid and solid regions greatly differ. The core of the incoming jet penetrated roughly 8 cm, after which the temperature dropped significantly. The tip of the torch nozzle experienced temperatures up to 317 ºC. The temperature decreased as it traveled down the length of the torch. This was observed experimentally with TC2.

The temperature of the fluid and solids along the mid-plane of the reactor had heat localized in the bottom of the chamber near the inlet jet as expected. The lower-middle portion of the downstream Inconel plate had the highest temperature of 100 ºC. With the inlet and environment conditions specified, the trash feed pipe did not have a significant increase in temperature. A large portion of this pipe remained at a fairly low temperature as the heat was quickly carried away into the environment. Heat from the torch spread from the torch cup and dropped with distance. The total pressure drop of the system was approximately 2.4 Pa. The results of the temperature profile of fluid and solid at the mid-plane are shown in Figure 8.

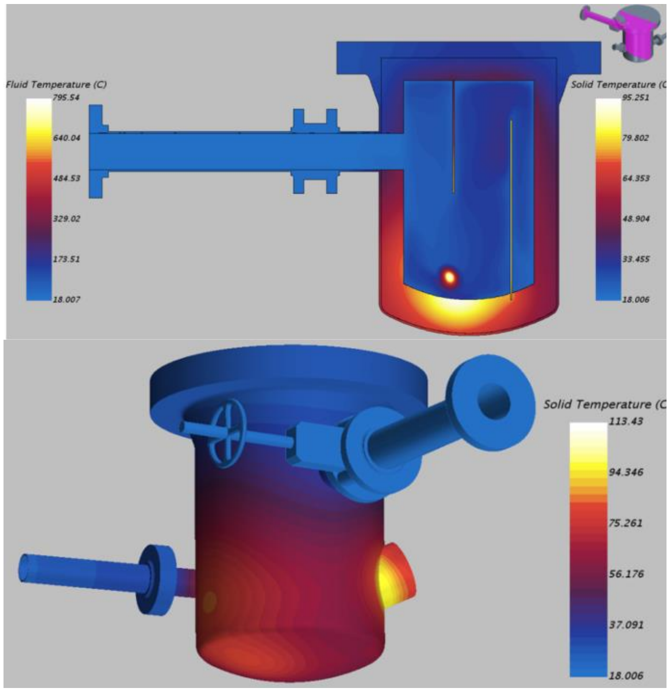

Figure 8. Top: Temperature profile of fluid and solid at the mid-plane. Bottom: Temperature profile on the steel case and outer pipes.

IV. Recommendations and Future Work

Future work with this torch should focus on studying the pressure, flow, and system variables in a facility with higher power service, in order to reveal conditions to achieve stable, long-duration torch operation, which would allow lower-power plasma arc operation. However, since high power was not desired for this technology demonstration, the future use of this specific AC torch for long-duration mission waste degradation is not recommended. Other plasma source recommendations to demonstrate feasibility of this technology include RF plasma, glow torch discharge, and spacial arc plasma. These torches may require lower power and can be operated continuously, with a 120 V standard power supply.

V. Conclusion

This project designed, built, and tested an AC plasma arc torch in a gasification system for plasma arc gasification applications. A waste feed system, reactor vessel, and post reactor gas processing system were successfully built and integrated with a novel low-power plasma arc torch and power supply. Two different plasma arc power supplies were tested and characterized with varying carrier gases, including Ar and air, at varying flow rates and pressures. Cotton washcloths and paper were exposed to the plasma arc, showing degradation with only a few minutes of exposure. In approximately 2 minutes of plasma arc exposure, 41.49 g of paper lost 0.5% of its mass. However, this was not proved scalable since the torch was unable to operate at long durations due to the power load need for operation. Designing the power supply was the main challenge in this project. Although this plasma torch was successfully operated for short periods of time, the power supply did achieve low power operations for long duration operation. It is believed that future waste degradation studies with plasma arc gasification should be performed with other plasma torch sources. Even though large-scale plasma arc gasification has been demonstrated industrially, low-power plasma arc gasification for waste degradation for space is at a lower technology readiness level (TRL) than initially thought. Plasma physics, let alone the degradation of complex waste feeds found in human space travel, is a challenging science. This project has achieved further knowledge of plasma gasification, but testing with other small-power plasma arc loads would need to be demonstrated in order to see whether plasma is comparable to the other waste conversion technologies studied in the TtG Project.

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