CONTINUOUS POLYETHYLENE PYROLYSIS FOR HYBRID FLAME/CVD SYNTHESIS
OF CARBON NANOTUBES

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CHAPTER 2

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ABSTRACT:

A system was designed to integrate the continuous feeding of polyethylene for pyrolysis into the hybrid flame/CVD carbon nanotube (CNT) synthesis process previously developed in this laboratory. Following the completion of the stainless steel design and machining operations, the polyethylene dispenser, screw conveyor, pyrolysis chamber, venturi flame holder, particle filter, synthesis chamber and dual-zone heating system were successfully integrated for full operation. A water cooling unit was incorporated with the screw conveyor to ensure flawless delivery of polyethylene to the pyrolysis chamber, as well as a support system to suspend the CNT catalyst within the synthesis chamber. As with the previously developed process, the intended use of combustion effluent within the apparatus was to synthesize multi-walled CNTs using stainless steel wire mesh. This was facilitated by an extensive study of the effluent produced with this continuous feeding system at varying system settings and in comparison to the previous apparatus, followed by a determination of the system parameters, which result in conditions most favorable to multi walled CNT growth.
CHAPTER 1

1. Introduction:

The research described herein serves as a continuation of the work described in “Synthesis of carbon nanotubes by sequential pyrolysis and combustion of polyethylene” written by Chuanwei Zhuo and published in the August 2010 Elsevier Carbon journal. The experiment detailed in this already published paper demonstrates the “viability of partial conversion of a readily-available waste stream to the value-added product of CNTs”. It serves as a first-generation attempt to bring carbon nanotube (CNT) production from the laboratory to an industrial scale, in both a fiscally feasible and environmentally responsible manner, in response to the perceived future demand for CNTs in a variety of applications. The research in this second-generation experiment seeks to improve upon the previously developed CNT synthesis process by means of a new apparatus strategically designed to remove the restrictions of its predecessor, shown in Figure 1.

![Figure 1: Previous CNT Synthesis Apparatus](image)

The previous system consists of a fragile, one-piece, blown quartz tubular structure limited to 1 gram of plastic per experiment. The system uses a pyrolysis chamber, venturi, and filtered synthesis chamber, numbered 1, 2 and 3, respectively, in Figure 1, to produce multi-walled CNTs on a stainless steel 304 mesh catalyst. Though the published research proves it reliably and consistently functions as desired, it does not provide the product volume or running time necessary for full-scale industrial production of CNTs.
2. Experimental Apparatus, Materials, Procedures:

2.1 System Requirements

The first step in designing the new system was for the design team to establish requirements, which were determined to be the following:

The system:

- Shall be capable of continuously feeding plastic into the pyrolysis chamber at a rate of approximately 1 gram per minute to result in larger scale CNT synthesis, due to constant feed rate and prolonged run time.
- Shall be sealed to withstand back pressure in order to keep gases flowing downstream to the CO\textsubscript{X} and O\textsubscript{2} analyzers. A positive internal pressure would also prevent air from leaking into the flow path.
- Shall be capable of withstanding higher internal pressures than quartz, due to unknown the consequences of continuous pyrolysis and prolonged run time. Quartz, while able to withstand temperatures in excess of 1000°C, does not have the strength of other commonly available iron and nickel based metals. Although, an iron or nickel based metal does not have the low thermal conductivity of quartz, its yield strength at high temperatures ensures a significant factor of safety for the combustion chamber.
- Shall be up to 1000°C capable. Where the previous apparatus used temperatures in excess of 700°C, the new continuously feeding system must be able to function at even higher temperatures to ensure as close to 100% gasification of the plastic fuel in the pyrolysis chamber as possible.
- Shall fit entirely within fume hood, allowing full closure of the glass to protect the operator from CO in the effluent gas flow and any possible respiratory effects of CNTs, which have not been identified nor studied to date.
- Should be capable of feeding the LLDPE pellet size available from DOW, since preliminary testing of the plastic feeding system proved favorable to the size of the DOW pellets found in the laboratory.
- Should fit within a combination of the laboratory’s inventory of split tube, electrically heated furnaces. Since this new system could be sized to fit within a specific envelope,
there was no need to purchase a furnace specifically designed around the new system at a cost of several thousand dollars.

With these requirements established, the design team began to create a system to meet them as fully as possible.

2.2 System Design & Verification

The final system concept chambers consisted of a welded 304 stainless steel design, due in part to its ease of repair, its common availability on the market, and its significantly low raw material and manufacturing costs, all when compared to hand blown quartz. Also, since stainless steel tubing is available in many different standard diameters and wall thicknesses, it was very easy to size the welded assembly to fit within existing laboratory furnaces as desired. Two and three-inch diameter tubes were determined to fit within the Hi-Temp and ATS furnaces, respectively. A tubing wall thickness of .065 inches was chosen after a hand calculation, using Equation 1 for hoop stress in thin-walled cylinders, showed positive margin to the 0.2% yield strength up to several hundred psi of internal pressure. Since it was assumed the actual system internal pressure would be less than 100 psi, this was deemed adequate safety margin.

\[
\sigma = \frac{P \cdot r}{t}
\]

(Equation 1)

Where “\(\sigma\)’’ is hoop stress in the tube wall, “\(P\)’’ is internal pressure, “\(r\)’’ is the inside radius and “\(t\)’’ is the wall thickness.

An existing soot filter was identified to meet the size requirement for the Hi-Temp furnace, pending a diametrical reduction of its end flanges to mate with two inch diameter tube at either end of the filter, as shown in Figure 2. Welded adapter rings were designed to ensure proper connections at the tube-to-filter and tube-to-tube interfaces. Further dimensional details of the assembly are available in Appendix A, which contains detailed CAD drawings of all piece parts, in addition to an assembly drawing and assembly welding drawing.

The venturi flameholder was designed using a venturi oxygen jet penetration length calculation, Equation 2, from Lefebvre’s *Gas Turbine Combustion* in conjunction with the left half of the general equation for combustion of a hydrocarbon in oxygen, Equation 3, to obtain
the mass flow rate of oxygen required for a specific equivalence ratio.

\[ Y_{\text{max}} = 1.25d_j \cdot 10^{-3} \cdot J^5 \left( \frac{\text{mdot}_g}{\text{mdot}_g + \text{mdot}_{O2}} \right) \]  
(Equation 2)

Where “\( Y_{\text{max}} \)” is the jet penetration depth, “\( d_j \)” is the jet hole diameter, “\( J \)” is the momentum flux (a function of main flow path and jet gas velocities and pressures), “\( \text{mdot}_g \)” is the total mass flow rate in the main flow path, and “\( \text{mdot}_{O2} \)” is the flow rate of oxygen through the jet holes.

\[ x(C_a \cdot H_b) + x \left( \frac{1}{\phi} \cdot \left( a + \frac{b}{4} \right) \cdot O_2 \right) \]  
(Equation 3)

Where “\( x \)” is the number of mols of hydrocarbon and “\( \Phi \)” is the equivalence ratio.

For ideal mixing, if there are at least two jets opposite each other in the venturi, the desired penetration depth is, at a minimum, half the central thru-hole diameter. The goal of this calculation is to ensure that when oxygen from the jet holes (perpendicular to the main thru hole) enters into the primary flow path of nitrogen and gasified polyethylene, the oxygen fully penetrates and mixes with these gases. The complete calculations to determine the venturi flow path dimensions were performed in MathCAD and are attached in Appendix B.
Once the penetration depth calculation was complete, the venturi was machined from 304 stainless steel bar stock using a lathe to plane faces, turn weld preps for tube attachment, and drill the central thru hole. The jet holes for oxygen flow were cross drilled with equal circumferential spacing on a drill press. They were then counter-bored to allow for the concentric welding of a 3/16” diameter stainless steel tube span to each jet hole to be used as oxygen supply lines. A detailed drawing of the venturi flameholder is located in Appendix A2.

In addition to the main stainless steel welded assembly, a plastic feeding system is attached at its forward end to supply the pyrolysis chamber with plastic for gasification. A great deal of this project was spent completely redesigning an existing feeding system, before it was able to meet the desired feeding rate under continuous operation. The final plastic pellet feeding system consists of an integrated screw conveyor and pellet dispenser, shown in Figures 3 and 4, respectively. The screw conveyor system contains a ¾” auger bit within a tube, as the screw, the end of which is fitted to an electric motor. A voltage regulator connected to the motor controls the screw’s speed of rotation. It was found that that the DOW company’s linear low density polyethylene (LLDPE) pellets were a perfect fit for the threads of the auger bit, and were therefore chosen as a fuel source for the feeding system. The plastic pellet dispenser itself is made up of several different components. At the very top, an electric agitator motor is attached to a brass rod, which protrudes downward into a pellet hopper to ensure

![Figure 3: Screw Conveyor](image)
static friction does not prevent settling of the pellets as the hopper empties. A small hole at the bottom of the cylindrical hopper provides an exit for the plastic pellets and butts up against a rotating, circular slotted dispenser disk. The dispenser disk is attached to a variable electric motor and contains one hole near its outer edge. As the disk rotates, the hole passes by the exit of the hopper, pellets fall through the disk, and straight into the screw conveyor, which then carries them into the pyrolysis chamber.

The major challenge in redesigning the pellet dispenser, due mainly to the great deal of interfacing components, was making it capable of withstanding backpressure. It was not suspected that combustion in the pyrolysis chamber and venturi would result in a combined backpressure in excess of more than one atmosphere. However, if the system could not withstand any backpressure, the gasified plastic would not flow downstream towards the synthesis chamber as desired. The ideal method of sealing the dispenser was determined to be enclosing the entire system within a large plastic zipper seal storage bag. While this would eliminate the painstaking task of individually sealing all of the dispenser’s joints, it seemed unlikely that a thin plastic bag could withstand intense heat radiating from the end of the furnace running at 700°C just a few inches away. Therefore, the rotating dispenser disk was enclosed within a thick plastic box, the entire dispenser was sealed with RTV, and the feeding system was sealed to the stainless steel assembly with a clamped and face mounted
polytetrafluoroethylene (PTFE) o-ring seal. PTFE was chosen as the o-ring material due to its maximum operating temperature of 260°C, which is significantly higher than that of commonly used fluoroelastomer o-rings (200°C).

The third and final main component of this apparatus is an end cap with an integral catalyst support, which is at the aft end of the main stainless steel assembly, as shown in Figure 5. The end cap bolts to a specially designed flange, welded to the end of the stainless steel assembly, and uses a PTFE o-ring face seal to prevent effluent gases from leaking out of the primary flow path and oxygen from leaking in. Like the venturi, it was turned from 304 stainless steel bar stock. An o-ring groove was turned into the sealing face and a thru hole drilled and tapped to allow a fitting and hose to carry effluent gas downstream towards instrumentation for data acquisition. Two threaded stainless steel rods attach the end cap to a piece of stainless steel angle with a slot sized to fit a ceramic “boat”. When the 304 stainless steel mesh CNT catalyst is set in the boat, this support system suspends it within the synthesis chamber. Appendix A3 shows this component’s installed position in a CAD drawing of the final design.

Preliminary tests of the entire apparatus under operating temperature revealed a serious design flaw. Traces of CO and CO₂, indicative of combustion, were initially observed but subsided even as the dispenser could be observed dropping pellets into the screw conveyor. Disassembly revealed that since the screw protrudes into the furnace, it became hot enough to
melt the plastic pellets before they could get to the end and gasify within the pyrolysis chamber. This then prevented any further plastic from moving through the conveyor. Figure 6 shows one instance of this outcome.

Figure 6: Plastic Melted to Screw Conveyor

After several simplistic attempts failed to remedy the issue, it was clear more drastic measures were required to cool the screw. A water cooled jacket, depicted in Figure 7, was chosen to replace the tube surrounding the screw conveyor, due to successful use in a similar application for a coal combustion research project. Although there was no way to quantify the amount of heat a water cooled jacket would remove from the screw conveyor, it provided the most potential to eliminate this design flaw and could be integrated into the current system without rework of the main welded assembly. Its integration was facilitated by welding the cooling jacket to a main flange, through which cooling water could enter and exit a closed loop. The forward face of this flange seals to a PTFE o-ring on the plastic feeding system and the aft face holds another PTFE o-ring which, in turn, seals to the front flange of main welded assembly. The rest of the cooling device consists of three concentric stainless steel tubes, sized to leave a cylindrical water flow 0.060” thick (found to be sufficient flow in the similar application), and an end cap.

Like the venturi, the water cooled jacket’s main flange was turned from 304 stainless steel bar stock. It was then drilled through the center to allow the screw conveyor to pass through. Cooling water inlet and outlet holes were cross-drilled and tapped to allow for hose fitting attachment. The center thru hole was counterbored to center three concentric tubes, creating a cooling water flow path. As shown in Figure 7, this flow path design allows the cold inlet water to pass closest to the screw conveyor, maximizing heat removal. The tubes were
welded in place on the main flange and the cap was welded to the end face of the assembly, closing the cooling water loop. In an effort to protect the metal tubes from direct exposure to high temperatures within the furnace, the outermost tube was coated with Zircar high temperature ceramic insulation. When the system was run with the water cooled jacket installed, it proved more effective than anticipated. Removal of the screw conveyor from a 900°C oven after several hours showed no plastic melted to the screw bit and the bit itself was cold to the touch. Detailed machining and welding drawings of the water cooled jacket in Appendix A4 provide dimensions of the assembly.

**Figure 7: Water Cooled Jacket**

In addition to all previously described components, Figure 8 shows how the entire experimental apparatus in the laboratory included both O₂ and COₓ analyzers, used to measure contents of effluent gas, and PID controllers to maintain the desired furnace temperatures. Data acquisition hardware and software recorded readings from these analyzers. Figure 8 also shows how the apparatus fits within the fume hood with room to spare. This extra room proved beneficial because it allowed for complete removal of the screw conveyor for routine maintenance, as well as removal of the end cap with integral catalyst support for sample collection. The system is angled slightly downward in the downstream direction (left to right in Figure 8) to help melting plastic flow downstream into the hottest central zone of the furnace, with the intent of improving the percent of plastic gasified. Cooling water comes directly from
a valve within the fume hood and is monitored by a flow meter. Another valve within the fume hood provides cooling air jets to the PTFE o-ring that seals the end cap to the main assembly. This was necessary due to PTFE’s maximum operating temperature of 260°C and the synthesis chamber’s furnace temperature of over 700°C. These cooling air jets proved effective at keeping the o-ring within its temperature capability. Additionally, due to the laboratory’s lack of experience with continuous gasification of polyethylene and combustion of resulting hydrocarbons, pressure release valves and a flashback arrester were added to the venturi jet lines to ensure operator safety.

Figure 8: Laboratory Setup

3. Conclusions

Although designing this system presented several significant challenges, even a few surprises, in the end it proved to successfully operate as desired and met all of the requirements. The 304 stainless steel welded assembly and catalyst support system showed the expected thermal capability after hours of exposure to temperatures in excess of 900°C and withstood pressures generated from expansion of the gasified plastic. It fit within the laboratory’s existing split tube furnaces, as was the design intent, thus saving several thousand dollars and the lead time associated with the purchase of a new furnace. The plastic pellet dispenser performed its desired function well and, in conjunction with the screw conveyor and
water cooled jacket, proved to be capable of continuously feeding plastic into the pyrolysis chamber for extended periods of time (10mins +). Though not 100% airtight, sealing of the plastic feeding system withstood enough back pressure to generate a measureable amount of flow out of the synthesis chamber. Lastly, the entire apparatus, minus analyzers and data acquisition hardware/software, fit within the fume hood, leaving enough space to remove components, as required, for sample collection and periodic maintenance.

One aspect of the system where design improvement may result in performance enhancement is the PTFE o-ring seal at each end of the main welded assembly. The choice of PTFE as an o-ring material for its high temperature capability drove the design to use face mounted o-rings, as opposed to radially mounted o-rings, because of the relative stiffness of PTFE compared to that of fluoroelastomers. Face mounted o-rings, due to their very nature however, do not provide as much margin for misalignment as radially mounted o-rings. This made the system sealing very sensitive to slight adjustments and increased re-assembly time following a teardown inspection. A more effective sealing or component alignment method would improve sealing and increase internal pressure to drive combustion products downstream toward the analyzers.
CHAPTER 2

1. Introduction

To further develop the carbon nanotube (CNT) synthesis process previously developed in this laboratory and described in “Synthesis of carbon nanotubes by sequential pyrolysis and combustion of polyethylene” by C. Zhuo and published in the August 2010 Elsevier *Carbon* journal, the research described herein involves the use of a follow-on apparatus with improved durability and the ability to continuously feed itself polyethylene (PE) as fuel for subsequent CNT synthesis. The experiment detailed in the previously published paper demonstrates the “viability of partial conversion of a readily-available waste stream to the value-added product of CNTs”. The newly designed apparatus attempts to more closely resemble a scaled down industrial model, by demonstrating the viability of a system which uses the established process, along with the ability to provide itself a constant flow of fuel to operate continuously, as opposed to operating only in a size-limited batch mode.

The system schematic shown in Figure 1 provides an overview of the improved apparatus. Air and nitrogen supply lines feed into a main control board and flow meters

![Figure 1: System Schematic](image)
regulate their rate of run into the system. The air then travels through a flame arrester, splits into three lines, passes through pressure relief valves and into three equally spaced holes around the circumference of the venturi. The flame arrester, consisting of a screen and check valve, assures that any errant flame from the venturi will not travel backwards in the line and pressure relief valves provide a means of escape for any blowback resulting from a sudden pressure increase at the venturi. Nitrogen travels from the main control board and into the PE pellet feeding system, which consists of a dispenser and water-cooled screw conveyor, as a shielding gas to prevent oxygen from entering the system prior to the venturi. The PE pellet feeding system sends plastic directly into the pyrolysis chamber, which is heated by a \( \sim 900^\circ C \) split tube electric furnace to gasify the plastic. The plastic gasification releases hydrocarbons, which auto-ignite as they pass through the venturi and are suddenly mixed with oxygen. This flame produces a carbon rich exhaust which flows through a soot filter and into the CNT synthesis chamber at high temperature (\(+700^\circ C\)). It is this carbon rich exhaust that has the potential to settle in rings on a catalyst to produce CNTs at the proper gas concentration and temperature, as described in the aforementioned publication.

Once the effluent gas exits the synthesis chamber, it flows through a paper filter and condenser to protect the analyzers from particle and liquid contamination. It then goes to the analyzer control board. The analyzer control board regulates proper flow to the \( O_2 \) and \( CO_x \) analyzers and releases any excess into the exhaust as bypass flow. Bypass flow is released into the fume hood, as are the analyzer exit streams. An alternate line from the analyzer control board provides the \( CO_x \) analyzer with calibration gas as required.

2. Results

Initial runs of the completed apparatus were performed at several different settings to determine the optimal parameters for producing an effluent profile similar to the original, single-batch fed apparatus. A literature review of published research, including the research used to derive this specific CNT synthesis method, indicated that levels of CO between ten and twenty percent were required to produce CNTs. A variation of system parameters revealed that increasing the temperature of the pyrolysis chamber, as well as increasing the plastic feed rate, increases the effluent percentage of CO. Figure 2 shows an effluent profile for what were
Figure 2: Optimized Effluent Profile

determined to be the optimum system settings. The first furnace (pyrolysis chamber, venturi and filter) was set to 950°C, a higher temperature for pyrolysis than the original apparatus, but low enough to not test the materials’ thermal capability. A high plastic feed rate also increased levels of CO and the dispenser motor was set to 9V, the second to highest setting, to create a fuel rich condition at the venturi. A time delay of three minutes between when the plastic dispenser was turned on and, when air to the venturi jets was turned on, proved to be sufficient time to generate a buildup of polyethylene gases within the pyrolysis chamber. This ensured that when air to the venturi jets was turned on, there would be a sufficient amount of hydrocarbons to produce a flame and consume the oxygen, which would otherwise oxidize the catalyst samples, rendering them useless for CNT production.

While Figure 2 depicts the system’s optimized effluent profile to date, it is far from an exact match to the profiles in Zhuo’s published research, used to derive the CNT synthesis method this apparatus is based on. The initially high spikes in CO2 were not typical of the previous system’s successful CNT producing profiles. Figures 3a & 3b show a comparison of new versus old apparatus outputs, both from a single one gram batch of PE to make for an even comparison. To operate the new apparatus in single batch mode the dispenser was left turned
off, one gram of PE was set inside the water cooled jacket tube, and the screw was reinserted to push the plastic into the pyrolysis chamber. The profile in Figure 3a shows CO₂ percentages at equivalent levels to CO, as does Figure 2, whereas Figure 3b shows CO levels twice that of
CO₂ for the old apparatus. It is important to note that the O₂ spike in Figure 3a is due to the period between the removal and reinsertion of the conveyor screw to insert a one gram PE batch, during which air was able to enter system for approximately one minute. It is not yet understood why, although it was also opened briefly to insert a single batch of PE, the profile of the apparatus from previous research in Figure 3b does not contain the same spike in oxygen concentration. However, a comparison of Figure 2 (continuous feeding) and Figure 3a (single batch) shows that high levels of CO₂ were present whether or not the new apparatus was opened to run a single batch. Figure 2 shows that high CO₂ levels still appear when the system remains shielded with nitrogen, closed and running under continuous feeding. Yet more intriguing is the fact that, as displayed in Figure 2, CO₂ percentages increase significantly prior to the venturi flow being turned on, introducing oxygen to the system. This would indicate that oxygen is introduced to the system prior to the venturi being switched on. But where could it enter the system?

One possible source of air is a leak into the flow path. This seems unlikely, however, due to the care taken to seal the system and the fact that it is constantly being purged with nitrogen during each experiment. It is known that small leaks exist due to the complex geometry and number of joints involved with sealing the plastic feeding system. To account for this, nitrogen flow into the dispenser and conveyor was set to 4lpm, for which a flow of roughly 1lpm was observed exiting the system. When this nitrogen shielding gas was the only flow going into the system (i.e. dispenser and venturi turned off), the oxygen analyzer read zero. This suggests the system has enough nitrogen flow to be pressurized internally, thus causing any leaks to be directed outwards and preventing air from entering, which is the desired intent. Another possibility, that has not yet been investigated, is there are pockets of moisture or air trapped within the low-density PE pellets. This could be due to the fact that since these pellets are resin intended for industrial molding applications, they have not been fully dried in their current state.

After many unsuccessful attempts to eliminate the appearance of CO₂ levels, it was decided that before further effort was spent to eliminate the condition, samples should be collected to determine whether or not the new apparatus is capable of producing CNTs as well
as the previous apparatus. Strips of fine 304 stainless steel mesh, the same material used as a catalyst for multi-walled CNT production in the previous apparatus, were placed within synthesis chamber after both furnaces were fully heated. The first furnace, covering the pyrolysis chamber, venturi and soot filter, was set to 950°C, as previously noted. The second furnace, surrounding the synthesis chamber, was set to an internal temperature of approximately 750°C, because the previously completed research found proper CNT synthesis required temperatures above 700°C. Samples were removed from the synthesis furnace after it cooled to less than 300°C, so as not to oxidize any CNTs present on the catalyst. Figure 4 shows SEM results for one of the most populated samples taken. The SEM image on the right shows a plethora of carbon nanostructures on the surface of the wire mesh at 10μm resolution. Subsequent inspection by TEM revealed these carbon structures to be solid, as opposed to hollow CNTs. Since the effluent profile under which they were synthesized does not show high levels of CO, this did not come as a surprise.

**Figure 4: SEM Results**

Figure 5 provides an example of TEM results, which show CNTs (identified as hollow by their translucent centerlines and darker outlines) produced using this apparatus. It should be noted, however, that while the results shown in Figures 4 and 5 provide some level of substantiation for this apparatus’ ability to produce CNTs, these results were not typical and, in
the case of Figure 5, were found only by way of a lengthy investigation. Upon investigation, many samples from a variety of conditions showed only carburized stainless steel mesh.

![Figure 5: TEM Results](image)

3. Conclusions

It is clear that the newly developed, continuously fed apparatus produces carbon structures of varying quality and does not currently produce results as similar to those of the previous system as intended or desired. Studies are currently underway to describe the phenomenon which produces significant CO₂ prior to what is believed to be the first point in time oxygen enters the system. The research described herein does demonstrate that continuous polyethylene pyrolysis produces effluent profiles suitable for synthesis of carbon nanostructures and that a higher dispenser feed rate increases effluent CO levels. Since the system as a whole behaves differently than the previous single batch setup, further work is required to complete optimization for reliable production of multi-walled CNTs and to explore the possibility of single-walled CNT synthesis. Further work on the system hardware itself, possible improvements, and trade studies, which may provide greater insight to its operation, include but are not limited to: use of a fluoroelastomer o-ring at the forward seal instead of PTFE due to decreased local temperature from the water cooled jacket, improved sealing of the plastic dispenser and screw conveyor, and gas chromatography analysis of the effluent to obtain a full list of constituent gases.
APPENDIX A: Machining & Welding Drawings
APPENDIX A4: Water Cooling Jacket CAD Drawing(s)
NOTE: ALIGN HOLES IN ITEM 1 WITH HOLES IN ITEMS 4 & 5, RESPECTIVELY, PRIOR TO WELDING ITEM 1 TO ITEMS 4 & 5.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ø2.5” 304SS Round Rod</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Ø1.375” 304SS Round Rod</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Ø0.875” x 0.065” Wall 304SS Tube</td>
<td>1</td>
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<tr>
<td>4</td>
<td>Ø1.125” x 0.065” Wall 304SS Tube</td>
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<td>5</td>
<td>Ø1.375” x 0.065” Wall 304SS Tube</td>
<td>1</td>
</tr>
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</table>

SCALE 1:1.2

TITLE: Water Injector Welding

PAGE 30
APPENDIX B: Venturi Calculations from MathCAD
Venturi oxygen jet penetration length calculations from Lefebvre, A., *Gas turbine combustion*. (CRC, 1998) where "g" refers to the central thru hole, and "j" refers to the round jet(s) of oxygen:

\[ d_g := 12.7 \]  
\[ d_j := 1.587 \]  
\[ n_j := 3 \]  
\[ \Delta t := 30 \text{ seconds} \]  
\[ Q_{N_2} := 1 \]  
\[ Q_{O_2} := 0.595 \]  
\[ m_{PE} := 0.75 \]  
\[ \rho_{gN_2} := 1251 \text{ g/m}^3 \]  
\[ \rho_{jO_2} := 143 \text{ g/m}^3 \]  
\[ \rho_{PE} := 0.92 \text{ g/cm}^3 \]  
\[ m_{dot_{gN_2}} := \frac{Q_{N_2} \cdot 28}{60 \cdot 22.4} \]  
\[ m_{dot_{gN_2}} = 0.021 \]  
\[ m_{dot_{gPE}} := \frac{m_{PE}}{\Delta t} \]  
\[ m_{dot_{gPE}} = 0.025 \]  
\[ m_{dot_g} := m_{dot_{gN_2}} + m_{dot_{gPE}} \]  
\[ m_{dot_g} = 0.046 \]  
\[ V_{gPE} := \frac{m_{PE} \cdot 1000}{\rho_{PE}} \]  
\[ V_{gPE} = 815.217 \text{ cm}^3 \]  

mass flow rate of nitrogen gas, where 28 is the molecular weight of nitrogen and there are 22.4 liters/mol at STP

mass flow rate of polyethylene gas

total mass flow rate of gas

volume of polyethylene vapor after expansion by one thousand times within the time period
\[ A_g := \frac{\pi \cdot d_g^2}{4} \quad \text{mm}^2 \quad \text{flow area of central thru hole} \]

\[ A_g = 126.677 \]

\[ U_{gN_2} := \frac{Q_{N_2} \cdot .001}{A_g \cdot 10^{-6} \cdot 60} \quad \text{m} / \text{s} \]

\[ U_{gN_2} = 0.132 \]

\[ U_{gPE} := \frac{V_{gPE} \cdot 10^{-6}}{A_g \cdot 10^{-6} \cdot \Delta t} \quad \text{m} / \text{s} \]

\[ U_{gPE} = 0.215 \]

\[ U_g := U_{gN_2} + U_{gPE} \quad \text{m} / \text{s} \]

\[ U_g = 0.346 \]

\[ \text{mdot}_{jO_2} := \frac{Q_{O_2} \cdot 32}{60 \cdot 22.4 \cdot n_j} \quad \text{g} / \text{s} \quad \text{mass flow rate of oxygen gas, where 32 is the molecular weight of oxygen and there are 22.4 liters/mol at STP} \]

\[ \text{mdot}_{jO_2} = 4.754 \times 10^{-3} \]

\[ A_j := \frac{\pi \cdot d_j^2}{4} \quad \text{mm}^2 \quad \text{flow area of jet hole(s)} \]

\[ A_j = 1.979 \]

\[ U_{jO_2} := \frac{Q_{O_2} \cdot .001}{A_j \cdot 10^{-6} \cdot 60 \cdot n_j} \quad \text{m} / \text{s} \]

\[ U_{jO_2} = 1.681 \]

\[ \rho_g := \frac{\text{mdot}_g}{\text{mdot}_{gN_2}} \quad \text{g} / \text{m}^3 \quad \text{uses ideal gas law ratio to find total density of gas (polyethylene vapor and nitrogen)} \]

\[ \rho_g = 2.752 \times 10^3 \]

\[ J := \frac{\rho_{jO_2} \cdot (U_{jO_2})^2}{\rho_g \cdot U_g^2} \quad \text{momentum flux} \]
\[ J = 12.262 \]

\[
Y_{\text{max}} := 1.25 d_j 10^{-3} J^{-5} \left( \frac{\text{mdot}_g}{\text{mdot}_g + \text{mdot}_j O_2} \right) \]

penetration length (needs to be a minimum of half the central thru hole diameter if there are at least two jets opposite each other in the venturi)

\[
Y_{\text{max}} = 6.296 \times 10^{-3} \quad \text{m}
\]

\*Where the flow rate of oxygen comes from the left half of the general equation for the combustion of a hydrocarbon in oxygen, which is:

\[
x (C_a \cdot H_b) + x \left[ \frac{1}{\phi} \left( a + \frac{b}{4} \right) O_2 \right]
\]

where is the equivalence ratio and \( x \) is the number of mols of hydrocarbon

\[
C_2H_4_{\text{mol}} := \frac{1}{(12.01072 + 1.007944)}
\]

dividing 1 g/min of ethylene by molecular mass of ethylene converts grams to mols

\[
O_2_{\text{mol}} := C_2H_4_{\text{mol}} \frac{1}{4} \left( 2 + \frac{4}{4} \right)
\]

use general combustion equation to determine mols of oxygen required for specified equivalence ratio

\[
Q_{O_2} := O_2_{\text{mol}} 22.4 \quad \text{lpm}
\]

convert mols of oxygen to liters

\[
Q_{O_2} = 0.599
\]