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# Design, Fabrication and Testing of a Pressurized Oxy-Coal Reactor Exhaust System

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Design, Fabrication and Testing of a Pressurized Oxy-Coal Reactor Exhaust System

Aaron Bradley Skousen

A thesis submitted to the faculty of  
Brigham Young University  
in partial fulfillment of the requirements for the degree of  
Master of Science

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## ABSTRACT

### Design, Fabrication and Testing of a Pressurized Oxy-Coal Reactor Exhaust System

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One of the challenges facing engineers is to provide clean, sustainable, affordable and reliable electricity. One of the major pollutants associated with coal combustion is CO<sub>2</sub>. A proposed technology for efficiently capturing CO<sub>2</sub> while producing electricity is pressurized oxy-combustion (POC). The first objective of this work is to design, build and demonstrate an exhaust system for a 20 atmosphere oxy-coal combustor. The second objective of this work is to design and build mounts for a two-color laser extinction method in the POC. The POC reactor enables the development of three key technologies: a coal dry-feed system, a high pressure burner, and an ash management system. This work focuses on cooling the flue gas by means of a spray quench and heat exchanger; controlling the reactor pressure and removing ash from the flue gas. Designs and models of each component in the exhaust systems are presented. Methods to test and assemble each system are also discussed. The spray quench flow rate was measured as a function of pump pressure. Theoretical models for the required amount of water in the spray quench, the flue gas composition, the length and number of tubes in the heat exchanger, and the cyclone collection efficiency are presented. The combined exhaust system is assembled and ready to be tested once issues involving the control system and burner are resolved.

Keywords: two-color laser extinction method, pressurized oxy-coal, combustion

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## 1 INTRODUCTION

One of the challenges facing engineers today is to provide clean, sustainable, affordable and reliable electricity. Coal is used to supply 38 percent of electricity worldwide [1] and the worldwide demand for electric power is increasing each year [2]. When fossil fuels burn, they produce undesirable pollutants like CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>. It has been projected that in the next 25 years will increase as a direct result for the rising demand for electricity [2].

While it is inevitable that CO<sub>2</sub> will be produced when burning fossil fuels, it has been proposed that CO<sub>2</sub> capture can be enabled using oxy-combustion. Burning coal with oxygen instead of air (oxy-coal combustion) produces a high concentration of CO<sub>2</sub> in the exhaust, which is more easily separated and compressed into a liquid [3]. The most common method of producing oxygen is cryogenic air separation. This method can be used to produce oxygen at a high pressure. Pressurized oxy-combustion enables improved efficiency because the inlet oxygen pressure is retained, and the exhaust CO<sub>2</sub> requires less compression to produce a liquid, which can be transported in a pipe and injected underground. Pressurized oxy-coal combustion can also reduce capital cost and equipment size and increase heat and mass transfer [3].

The Department of Energy (DOE) awarded Brigham Young University a grant to build and test a dry-feed pressurized oxy-coal combustor (POC) [4]. For the reactor to function there needs to be a means of cooling combustion gases, capturing fly ash particles and disposing of waste heat.

The first objective of this work is to design, fabricate and test an exhaust system for a 100 kW, 20 atm, pressurized oxy-coal combustor (POC). The primary components of the exhaust system include a spray cooling system, heat exchanger, and cyclone. The second objective is to design and fabricate mounts for optical equipment on the reactor for two-color laser extinction measurements during oxy-coal combustion.

## 2 LITERATURE REVIEW

Coal has traditionally been burned at atmospheric conditions with air. The concept of oxy-combustion was proposed in 1982 [5] as a means of producing CO<sub>2</sub> for enhanced oil recovery, where oxygen is used as the primary oxidant instead of air. Removing nitrogen from the oxidizer decreases the oxidizer volume by 79% and produces exhaust gas concentrations of on the order of 50 - 70% CO<sub>2</sub> depending on the carbon to hydrogen ratio of the coal [6]. The H<sub>2</sub>O is readily condensed leaving a very high concentration of CO<sub>2</sub> which can be compressed into a liquid phase and can be economically transported and reliably sequestered.

Atmospheric Oxy-coal combustion has been demonstrated from laboratory scale to industrial scale [3, 7, 8, 9, 10]. Two reviews identifying the advantages and challenges for oxy-coal combustion are given by Kenarsari and Wall [11, 12]. The most significant issue found is the cost of separating the O<sub>2</sub> from air and compressing the CO<sub>2</sub> [13]. Demonstrations suggest a loss in efficiency of 9% of the total plant power output [14]. There are several technical challenges to burning coal with oxygen. In order to retrofit existing power plants, the oxygen must be mixed with CO<sub>2</sub> to control the flame temperature. The CO<sub>2</sub> must be recycled from the flue gas which contains water vapor and fly ash. The heat transfer profile of the boiler can be changed by using oxygen to increase the radiative heat transfer due to higher combustion temperatures [15].

Pressurized oxy-coal combustion (POC) can reduce the cost and increase the efficiency of the process. The process provides an opportunity to increase the temperature of waste heat within the flue gas condensate, reduce equipment size, increase heat and mass transfer and increase chemical reaction rates [16]. The increased efficiency is due to the reduction in the parasitic load of the compression system and recovering latent heat in the flue gas moisture [3] [17]. Oxygen is not allowed to expand before combustion only to be re-compressed after combustion. The high gas density in POC increases heat transfer. This can lead to decreased capital costs in the heat exchangers and economizer in the boiler, by reducing heat transfer surfaces and boiler size [18, 19]. Higher residence times in high pressure oxy-combustion can reduce capital cost. Residence time is inversely proportional to the volumetric flow rate. As the pressure increases in the flue gas, the volume flow rates decrease, which can be accommodated by a smaller boiler. A higher residence time can also lead to improved burn out of fuel char, which reduces the number of particulate [16].

Pressurized oxy-coal combustion presents several challenges including: feeding coal feed at elevated pressure, pressure vessel constraints and flue gas clean up [16]. Two options for the coal feed are slurry or dry-feed systems. A slurry requires the water that conveys coal to be evaporated as part of the combustion process. This lowers the useful energy that can be recovered from the exhaust gas. Dry feed systems of pulverized fuels have not been demonstrated. Coal must be pulverized before it is burned. Once it is pulverized, it will fuse back together at pressure, unless conveyed in a carrier gas. Compressors for two-phase flows have wear issues. Suspending pulverized coal uniformly within the carrier gas is difficult and makes it problematic to maintain an even fuel flow rate. Pressure vessels are expensive and are required to be pressure stamped. It is difficult and costly to remove particulates at high pressure and ash

cleanup is needed for the overall system. There is little known of the geological issues and no regulatory consensus on the purity of CO<sub>2</sub> required for geological storage [16].

The University of Washington in St. Louis constructed a pilot scale 100 kW<sub>th</sub> staged pressurized oxy-coal facility [20]. The coal feeder is a pressure vessel that uses a hopper with a gravimetric twin screw feeder to allow for gravity feeding of coal into the burner. A horizontal vibrating linear feeder maintains a uniform feed rate of fuel. The facility operated with a methane/coal fuel at pressures less than 4 bar. An Italian utility company, ENEL (Ente Nazionale per l'Energia eLettrica) performed several tests on a 5 MW<sub>th</sub> boiler working at 4 bar. The fuel was feed with a water slurry. Molten slag was quenched in a water bath and coal ash was removed as vitrified inert material. The facility still has the ability to burn low grade fuels such as coals with high ash content and tar sands [21]. Southeast University in China performed simulations on an existing 300 MW circulating fluidized bed to retrofit it to high pressure oxy-coal combustion up to 435 psi. The models compared the efficiencies of the air separation unit, the CO<sub>2</sub> purification unit and the recirculating compressor and how they depend on pressure. Their models found an ideal pressure of 160 psi as an operating condition for the highest net efficiency of the boiler [19].

The Department of Energy (DOE) is focusing on driving costs down and collecting data for advanced coal-based power systems. They have issued solicitations for proposals that improve the performance of pressurized oxy-combustion systems. One of the objectives of the applied combustion research group at Brigham Young University is to demonstrate key technologies useful for the development of a POC. This will be completed by building a first-of-a-kind, 100 kW pressurized oxy-coal reactor. Washington University has completed a CFD model of a 385 MW oxy-coal reactor, which they suggest is scalable to power plant production

[22]. There are few facilities that operate with pressurized oxy-coal combustion in the world [16, 20, 21].

Understanding and being able to predict radiative heat transfer is critical for the design and operation of oxy-coal boilers. Coal particles play a vital role in the radiative heat transfer of a reactor. One of the primary particle participants is soot, which is formed in fuel rich regions surrounded by a flame. Soot can be reduced or eliminated in coal flames by implementing various mixing strategies, while coal char and ash particles cannot. It is therefore of interest to determine if radiative heat transfer is resulting from coal, char and ash or from soot. A two-color extinction method has been performed at atmospheric conditions to determine the amount of soot present in a coal flame [23]. This measurement has not been performed in coal flames at high pressure. This method will be investigated in the POC to determine if it can be implemented at 20 atm. The POC will also investigate a diffusion burner, ash management by slagging and how to implement a dry-feed system with CO<sub>2</sub> at high pressure.



### **3 DESIGN METHODS**

The method used for designing, fabricating, and testing the exhaust system components for the Pressurized Oxy-combustor (POC) are outlined in this chapter. The method followed was to first, identify design requirements and constraints; second, select a design concept; third, generate engineering calculations based on simple models in order to size components; fourth, order, fabricate, and install the components; and finally, test individual components and the complete exhaust system.

#### **3.1 Design Requirements and Constraints**

Design requirements and constraints for the exhaust system are shown below in Table 3-1. These constraints were developed during weekly design reviews based on what was promised in the Department of Energy grant DE-FE0029157. The basic requirement is to produce a 100 kW<sub>th</sub> Oxy-Coal reactor that operates at 20 atm. The reactor will be used to investigate key pressurized oxy-coal technologies including 1) a dry feed system, 2) an oxy-coal burner, and 3) an ash management system.

Table 3-1: Design requirement for exhaust system.

Design Requirement	Imperial Units	S.I. Units
Reactor Pressure (20 atm)	294 psig	2.02 MPa
Thermal Output	341,200 BTU/hr	100 kW
Maximum Diameter of Pressurized Exhaust Parts	6 in	152.4 mm
Total Footprint	17 ft <sup>2</sup>	1.58 m <sup>2</sup>
Stainless Steel Max Temp. at 1 atm.	1800 °F	1255.4 K
Electronic Control Valve Max Temp.	400 °F	477.6 K
Heat Exchanger Pressure (20 atm)	294 psig	2.02 MPa
Cyclone Pressure (1 atm)	14.7 psig	101 kPa
Cyclone Particle Size Removal (> 10µm)	99%	
Minimum Continuous Operation	12 hrs.	
Minimum Time Between Cleaning	48 hrs.	

As noted in Table 3-1, requirements for the exhaust system include the following items. In order to fit within the existing space, the exhaust system needs to occupy a floor space of 17 ft<sup>2</sup> or less. Codes require that vessels larger than six inches in diameter (152.4 mm) be inspected, stamped, and certified. For this reason, it was desirable that all components in the exhaust be six inches in diameter or smaller. A 6 inch (152.4 mm) stainless steel pipe can operate safely at 1 atmosphere of pressure if the temperature remains below 1800 °F. This sets the limit for uninsulated pipe and the heat exchanger. Commercially available, electronically controlled valves need to operate at or below 400 °F. In order to recycle flue gas using a blower, particles larger than 10 µm would need to be removed. A goal was set for a minimum of 12 hours of continuous operation and 48 hrs between exhaust component cleanings.

### 3.2 Design Concepts

The design requirements led to the concept shown in Figure 3-1 for the reactor and exhaust system. The design consists of a main reactor pressure vessel, which is refractory lined with optical and probe access points along the axial direction. The flue gas exits through a refractory

lined port, followed by a water spray quench, a shell and tube heat exchanger, control valves and a cyclone. The components upstream of the control valve will be at or near reactor pressure and the components downstream of the control valve will be at a slightly negative gauge pressure.

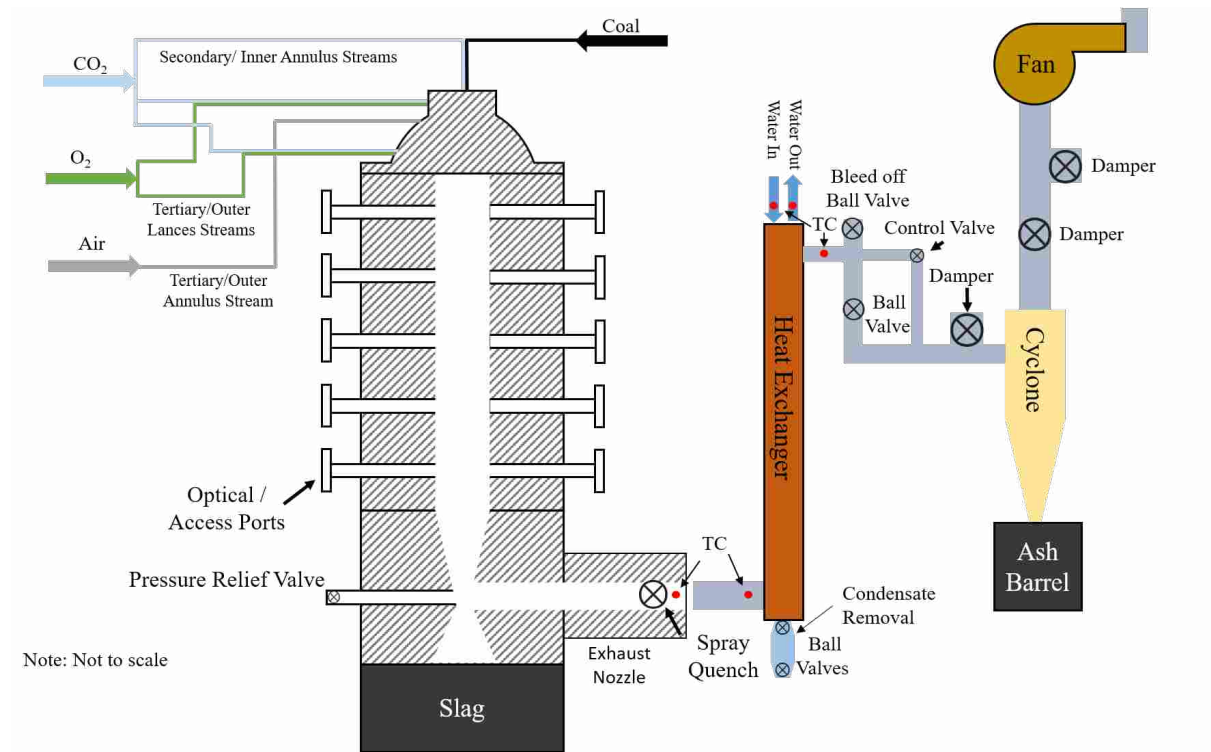


Figure 3-1: Schematic of POC reactor with exhaust system.

The reactor is designed to slag so that the bulk of the ash will be collected at the bottom of the reactor making it easier to clean, while increasing the life expectancy of the refractory. The rest of the components downstream of the exhaust nozzle are not designed to slag and do not need refractory. This requires lowering the outlet temperature, which is done with a spray quench.

A heat exchanger is needed to cool the flue gas down to temperatures acceptable for electronically controlled valves. A shell and tube heat exchanger was selected, based on its small footprint and high efficiency. A cyclone was added to remove the bulk of particles remaining in

the flue gas for particle sampling and analysis. Dampers allow the cyclone to be operated at a higher flow rate than exists in the reactor by adding dilution air.

### **3.3 Models**

In order to size components of the basic design, several models were utilized. The first was an energy balance and flow model of the reactor that produced exhaust flow rates, temperatures and compositions for the entrance of the exhaust system. Next, a simple energy analysis for the spray evaporation was used to size the spray nozzle. A classic NTU shell and tube heat exchanger model was used to size the heat exchanger components. The final model was used for the design of the cyclone separator. Each of these models will be described in the following sections.

#### **3.3.1 Reactor Flow and Heat Transfer Model**

Dr. Adams [24] used the Reaction Engineering International SteamGen Expert process model and in house calculations to perform heat transfer calculations and to find the composition of the flue gas at the exit of the reactor. Utah, Skyline coal, was used for the analysis and has been selected as the coal to be used in the POC. Results from their analysis relative to the exhaust are listed in Table 3-2. Initially, two different coals were selected for use in the reactor. These are Wyoming, Powder River Basin (PRB), and Utah, Skyline. Later, it was found that the PRB coal was difficult to feed and that Skyline coal would be the target coal used for initial testing. The coal type determines the amount of oxygen required and the temperature at which coal slags. The slagging temperature of coal is dependent upon the chemical composition of the ash and can range from 1160-2780 °F. The slagging temperature, or temperature required to produce a viscosity of 250 poise, for Skyline coal is 2330-2400 °F [24] [25] . This temperature

became a lower limit for the exit gas temperature. The refractory and metal shell must operate below 3400 °F and 450 °F respectively. Using these maximum and minimum refractory temperatures and maximum shell temperature, SteamGen Expert was run to determine flow rates that would keep the wall and gas temperatures within these limits. A relatively large amount of CO<sub>2</sub> was required to keep the temperature low enough to avoid reaching the shell temperature limit. The incoming reactor flow rates predicted by SteamGen Expert were: 27.12 lb/hr coal, 65.6 lb/hr O<sub>2</sub>, and 217 lb/hr CO<sub>2</sub>. For this inlet composition, the predicted outlet temperature was 3080 °F and with an exit refractory wall temperature of 2880 °F [26]. This was acceptable for both refractory and shell temperature. In the event the reactor is run at half the design thermal power, flow rates and temperatures were also predicted as shown by the lower flow rates in Table 3-2 demonstrating the reactor could operate over a range of operating conditions. The results from the SteamGen Expert model become inputs for the exhaust system.

Table 3-2: Constraints and results for the flow exiting the POC.

Model Constraints	Imperial	S.I.
Coal Type	Skyline	
Min. Reactor Exit Temperature (Slagging Temperature)	2400 °F	1589 K
Max. Refractory Temperature	3400 °F	2150 K
Max. Shell Temperature	440 °F	500 K
<b>Model Results</b>		
Coal Flow Rate Range	13.5-27 lbm/hr	6.1-12.3 kg/hr
Exhaust Total Flow Rate Range	159-308 lbm/hr	70-140 kg/hr
Spray System Inlet Temperature Range	2753-3080 °F	1785-1970 K

### 3.3.2 Spray Model

A model of the cooling spray was developed to determine how much water would be needed to cool the exhaust gas to a temperature acceptable for the heat exchanger. With the flow rate determined, the pump capacity and spray nozzle diameter could also be determined. The

spray model used the flue gas composition of CO<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>, and N<sub>2</sub> produced by the SteamGen Expert model. The model assumed products of complete combustion to characterize the input flow. The molar percentages are shown in Table 3-3. An energy balance was used between the liquid water and flue gas that entered the control volume as seen in Figure 3-2 and Equation 3-1. Boundaries of the control volume were assumed to be adiabatic, steady state and no work was done. The flue gas and water vapor were assumed to be in thermal equilibrium as they exited the control volume. Equation 3-2 expands the energy balance between the products of the reactor and water. Where,  $m_p$  is the mass flowrate of the products of the reactor,  $h_i$  is the enthalpy of the products at the inlet of the control volume,  $h_e$  is the enthalpy of the products at the exit the control volume,  $h_{fg}$  is the heat of vaporization of water,  $h(T_f)$  is the enthalpy of water at the exit flue gas temperature and  $h(T_{sat})$  is the enthalpy of water at the saturation temperature of water. The detailed analysis can be found in Appendix A.

Table 3-3: Mole fractions of flue gas.

	CO <sub>2</sub>	H <sub>2</sub> O	O <sub>2</sub>	N <sub>2</sub>
Composition of Exhaust Gas Exiting the POC (%)	87.07	9.71	2.74	0.46
Composition of Exhaust Gas after spray quench (%)	55.92	42.02	1.76	0.29

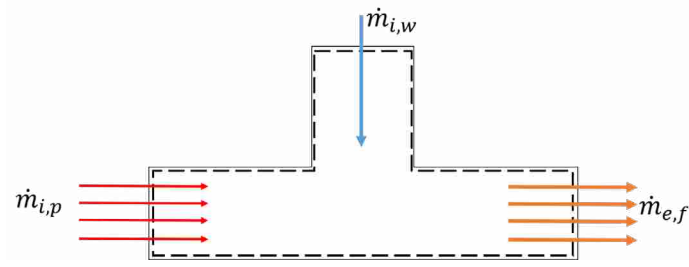


Figure 3-2: Schematic of spray quench energy balance.

$$0 = \sum \dot{m}_i h_i - \sum \dot{m}_e h_e \quad (3-1)$$

$$\dot{m}_p (h_i - h_e)_p = \dot{m}_w \left( h_{fg} + h(T_f) - h(T_{sat}) \right)_w \quad (3-2)$$

### 3.3.3 Heat Exchanger Model

The heat exchanger (HX) was modeled as a shell and tube heat exchanger as presented in Chapter 11 of Fundamentals of Heat and Mass Transfer by Bergman et al. [27] (Figure 3-3). The HX has one shell and two tube passes. The effectiveness of a heat exchanger (Equation 3-3) is defined as the actual heat transfer rate (Equation 3-4) divided by the maximum possible heat transfer rate (Equation 3-5). Where,  $\dot{m}_h$  is the flow rate,  $C_{p,h}$  the heat capacity, and  $T_{h,i}$  the temperature of the high temperature exhaust gas stream entering the heat exchanger.  $T_{c,i}$  is the temperature of the water coolant as it enters the heat exchanger. When two streams are present in a heat exchanger, each flow has a capacity for heat storage equal to the flow rate times the specific heat ( $\dot{m}C_p$ ). The smaller of these heat capacities is the limiting flow designated by Bergman et al. as  $C_{min}$ . In this case, it is desirable to make the exhaust gas flow with the lower heat capacity, so that it will have the largest temperature change.

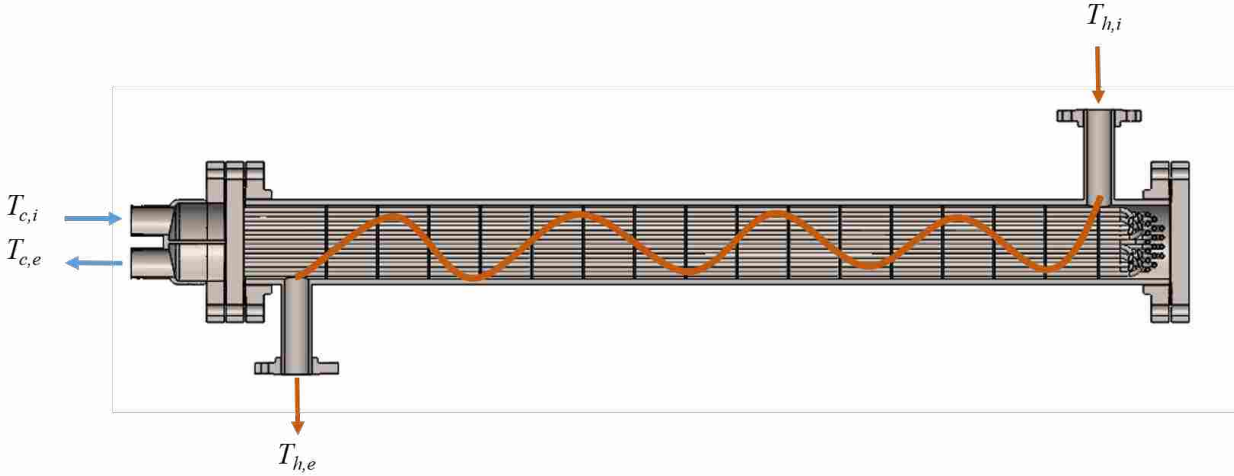


Figure 3-3: Shell and tube schematic.

$$\varepsilon = \frac{\dot{q}}{\dot{q}_{max}} \quad (3-3)$$

$$\dot{q} = \dot{m}_h C_{p,h} (T_{h,i} - T_{h,e}) \quad (3-4)$$

$$\dot{q}_{max} = \dot{m}_h C_{p,h} (T_{h,i} - T_{c,i}) \quad (3-5)$$

Bergman et al. [27] explains that the effectiveness of a heat exchanger can be correlated using two dimensionless parameters,  $NTU$  and  $C_R$ .  $NTU$  (Equation 3-6) is the ratio of the heat transfer rate per degree of temperature difference between the fluids and the rate of heat transfer per degree of temperature change in the minimum heat capacity fluid.  $C_R$  (Equation 3-7) is the ratio of the rate of heat transfer per degree of temperature change in the minimum heat capacity fluid to the rate of heat transfer per degree of temperature change in the maximum heat capacity fluid.

$$NTU \equiv \frac{U A_0}{C_{min}} \quad (3-6)$$



$$C_R = \frac{C_{min}}{C_{max}} = \frac{\dot{m}_h c_{p,h}}{\dot{m}_c c_{p,c}} \quad (3-7)$$

In these equations,  $U$  represents the total heat transfer coefficient as represented by Equation 3-8.  $A_o$  is the total surface area of the outside of the tubes (Equation 3-9). The subscripts  $c$  and  $h$  are for cold and hot respectively.  $L$  is the total length of a tube and  $N$  is the number of tubes.

$$\frac{1}{UA_o} = \frac{1}{h_i A_i} + \frac{R_{f,i}''}{A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2 \pi k L} + \frac{R_{f,o}''}{A_o} + \frac{1}{h_o A_o} \quad (3-8)$$

$$A_o = \pi D_o N L \quad (3-9)$$

Equation 3-8 uses a thermal resistance analogy to determine the overall heat transfer coefficient. In the first term on the right-hand side,  $h_i$  is the convective heat transfer coefficient for the water in the tubes. It was found by using the Dittus-Boelter correlation (Equation 3-10) for a turbulent fluid in a smooth circular pipe in Bergman et al. [27]. In the second term,  $R_{f,i}''$ , represents the fouling resistance between the water and the tube of area  $A_i$ . In the third term,  $k$  is the thermal conductivity for the tubes of inner and outer diameters,  $D_i$ ,  $D_o$  and length  $L$ . The fourth term is the fouling resistance,  $R_{f,o}''$  from the flue gas to the tube. In the last term,  $h_o$ , is the convective heat transfer coefficient on the flue gas side, which was found from the Zukauskas (Equation 3-11) correlation for flow across banks of tubes Bergman et al. [27].  $C_1$  is 0.36,  $C_2$  is 0.93 and  $m$  is 0.6.

$$Nu_D = 0.23 Re_D^{4/5} Pr^{0.4} \quad (3-10)$$

$$\overline{Nu_D} = C_1 C_2 Re_{D,max}^m Pr^{0.36} \left(\frac{Pr}{Pr_s}\right)^{1/4} \quad (3-11)$$

Each configuration of heat exchanger has a different relationship between the overall heat transfer coefficient and its effectiveness. The correlation for NTU in a shell and tube heat exchanger with one shell and two passes are given in Equations 3-12 and 3-13.

$$NTU = -(1 - C_r)^{-\frac{1}{2}} \ln \left( \frac{E - 1}{E + 1} \right) \quad (3-12)$$

$$E = \frac{2/\varepsilon - (1 + C_r)}{(1 - C_r)^{\frac{1}{2}}} \quad (3-13)$$

After solving for NTU for a given heat exchanger, the length of the heat exchanger can be found as seen in Equation 3-14. The number of tubes were constrained by the size of the 6” pipe that the bank of tubes had to fit inside. This led to an optimum tube number of 25 that were 3/8” diameter. Appendix A explains in detail how the length of the HX was calculated. The 2 in the denominator of Equation 3-14 is due to the cooling tubes making two passes inside the shell of the HX. The heat exchanger was given a factor of safety to account for fouling and degraded operating conditions by extending the length of the HX.

$$NTU = \frac{UA_0}{C_{min}} \Rightarrow L = \frac{NTU * C_{min}}{U(N2\pi D_0)} \quad (3-14)$$

The equilibrium mole fraction of water vapor,  $Y_{H_2O}$ , in the exhaust is given by Raoult’s law as seen in Equation 3-15; where the mole fraction in the vapor phase is  $Y_{H_2O}$ , the saturation pressure,  $P^{Sat}$ , the total pressure P and the mole fraction of the water in the liquid phase by  $X_{H_2O}$ . The only species that can condense under these pressures and temperatures is H<sub>2</sub>O which makes  $X_{H_2O}$  equal to 1. The mole fraction of water in the exhaust as shown in Table 3-3 is expected to be 0.4202, which suggests that water in the exhaust at a total pressure of 20 atm. or partial pressure of 122 psi will begin to condense at 343 °F. This is below the expected temperature of the heat exchanger outlet but not below the temperature of the coolant and the tubes. It is

therefore expected that water will condense on the tubes of the heat exchanger and flow by gravity to the bottom of the heat exchanger. A means for draining this water from the heat exchanger is therefore required. It is difficult to estimate the amount of water that will condense on the tubes.

$$y_i = \frac{x_i P_i^{Sat}(T)}{P} \quad (3-15)$$

### 3.3.4 Cyclone Model

The cyclone was modeled using Equations in Ch. 9 of Air Pollution Control Engineering by De Nevers and literature from LTG Air Tech systems [28] [29]. Typically, cyclone dimensions such as height and cone angle are normalized relative to  $D_o$ , the outside shell diameter. These relationships, each relative to  $D_o$ , are shown in Table 3-4 with physical locations on a generic cyclone shown Figure 3-4 [28]. A flow rate of 283 ft<sup>3</sup>/min was chosen based on reactor output flow rates and exhaust fan capacity. The gas entering the cyclone is close to atmospheric pressure. A commercial cyclone capable of comparable flow rates was identified having a  $D_o$  of 11.02 inches [29]. The cyclone designed for this work was modeled after this commercial cyclone using the relationships contained in Table 3-4 and a  $D_o$  of 11 inches. The cyclone separator was manufactured instead of purchased commercially because the price of a manufactured cyclone was a quarter of the cost of buying a commercial cyclone.

There are two main models for determining a cyclone's efficiency. The models are block flow and mixed flow. Block flow assumes that the flue gas is totally unmixed. Mixed flow assumes total mixing of the flue gas at a cross section perpendicular to the flow in a device. The cut diameter is derived from the blocked flow efficiency. The cut diameter gives a measure of

the size caught and the size passed in a particle collector. An example of a cut diameter would be separating peas in a kitchen colander with uniform circular holes. The circular holes would be the cut diameter. The collection efficiency would be 100% for peas greater than the cut diameter and 0% for peas smaller than the cut diameter. Since coal fly ash and particulate are real particles, there is a percentage of particles that may or may not pass through for a given diameter [28]. The cut diameter is defined as the diameter of a particle for which 50% of particles will pass through and be collected. The cut diameter was calculated from the size of the cyclone and the flue gas properties as defined in Equation 3-16. The cut diameter for this cyclone was calculated as 3  $\mu\text{m}$ . The mixed flow efficiency of the cyclone was calculated to be 99% with particles greater than 10 $\mu\text{m}$  (Equation 3-17). The efficiency for block flow is shown in Equation 3-18.

In Equation 3-16;  $W_i$  is the width of the cyclone at the inlet,  $\mu$  is the viscosity of the flue gas,  $N$  is the number of turns that the flue gas traverses in the outer helix of the cyclone before entering the inner helix. De Nevers suggests to use  $N$  of 5 for most applications from experimental data.  $V_c$  is the velocity of the flue gas, which is determined by the inlet area of the cyclone ( $H \times W$ ), and  $\rho_{part}$  is the density of the particles.  $D$  is the particle diameter (Equation 3-17). A collection efficiency can be calculated at each diameter. The particle diameters of interest for coal fly ash range from 0.5-500  $\mu\text{m}$  [30].

$$D_{cut} = \left( \frac{9 W_i \mu}{2 \pi N V_c \rho_{part}} \right)^{\frac{1}{2}} \quad (3-16)$$

$$\eta_{mixed} = 1 - \exp\left( - \frac{\pi N V_c D^2 \rho_{part}}{9 W_i \mu} \right) \quad (3-17)$$

$$\eta_{block} = \frac{\pi N V_c D^2 \rho_{part}}{9 W_i \mu} \quad (3-18)$$

Table 3-4: Cyclone separator dimensions based on  $D_o$ .

Dimension	Relation
$D_o$	$D_o$
$W_i$	$D_o/4$
$H$	$D_o/2$
$H_1$	$D_o*2$
$H_2$	$D_o*2$
$D_e$	$D_o/2$
$S$	$D_o/2$
$D_d$	$D_o/4$

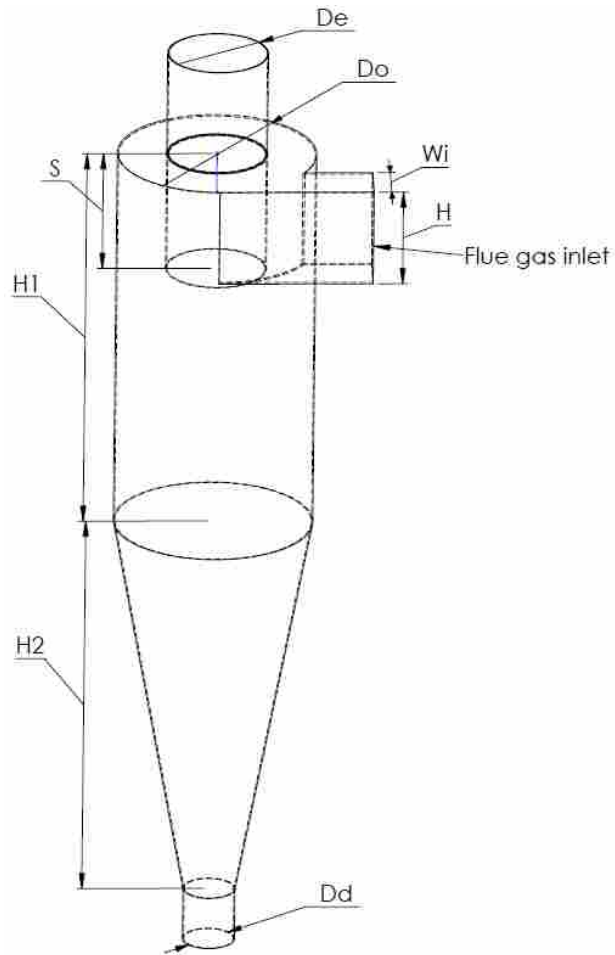


Figure 3-4: Schematic of cyclone separator [28].

## **4 DESIGN RESULTS**

Using the design requirements, constraints, and the models described in Chapter 4, detailed designs were generated for the exhaust system. System components were purchased, fabricated and assembled. The resulting exhaust system is presented in this chapter. The chapter begins with a description of the entire POC to provide context for how the exhaust system is integrated into the reactor. The chapter then provides details for each sub component of the exhaust system, starting with the exit port and following the flow downstream to the cyclone and exhaust fan. This chapter will provide a description of the basic dimensions, flow rates, components, and materials in each sub-system, as well as the purpose and operational process. Results from the modeling described in Chapter 3 will be used to support the design parameters selected and fabricated. Detailed drawings, part numbers and supplier information will be provided in Appendix B and C.

### **4.1 Entire POC Facility**

A schematic diagram of the entire POC facility is shown in Figure 4-1. The dashed portions in Figure 4-1 will be expanded further in this chapter. The green dashed lines represent the exhaust portion of the POC. The blue dashed lines represent the spray quench system. The orange dashed lines represent the laser mount system. Input flows of coal, CO<sub>2</sub>, O<sub>2</sub>, air, and natural gas will be supplied to the burner. It is expected that the reactor will be preheated using natural gas and air at atmospheric pressure, after which the pressure will be increased, and the

reactor will be moved to pulverized coal, O<sub>2</sub> and CO<sub>2</sub> operation. Coal will be fed with a dry feed system, which is novel for this project but is not a topic covered in this document. The maximum operating capacity is designed to be 100 kW<sub>th</sub>.

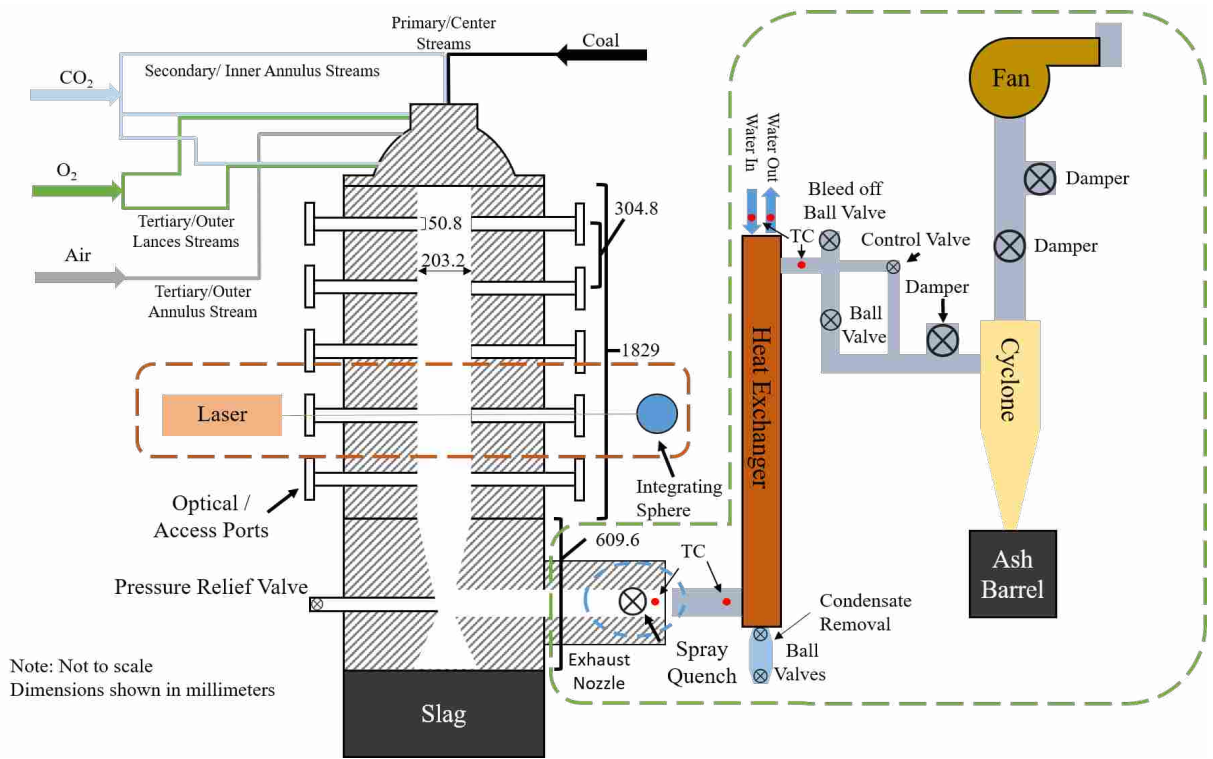


Figure 4-1: Overall schematic of reactor.

The outside shell of the reactor is broken up into three sections. The top section houses the burner. The burner has primary, secondary and tertiary lances. The primary line is a central tube that feeds coal with a carrier gas of CO<sub>2</sub>. The secondary line is an annulus that feeds a mixture of O<sub>2</sub> and CO<sub>2</sub>. There are eight tertiary lances that will supply O<sub>2</sub> and CO<sub>2</sub> around the center annulus. The flows will all be controlled remotely with mass flow controllers. The middle section of the reactor is the main section where combustion occurs. The wall temperatures will be above the slagging temperature to produce slag that flows to the bottom section. The outside shell is a 30 inch (0.762 m) carbon steel schedule 80 pipe. It is 6 ft long (1.83 m) for the main

section and 3 ft long (0.91 m) for the bottom section. The main section has 20 access ports. There are four columns of five vertical ports at 90 degrees intervals around the reactor. Two columns that are 180 degrees from each other, were cored out to have line of sight capabilities through the reactor. The two-color extinction method can be used on any of these five ports. The third column has two B thermocouples in each port to measure heat flux. The last column of ports was left undisturbed for future developments. There are three layers of refractory in the middle and bottom sections. The first layer is a 2 inch (50.8 mm) thick INSBOARD 2600 HD. The second layer is a 1 inch (25.4 mm) thick INSBOARD 2600 HD. The last layer is approximately 8 inches (203.2 mm) thick ULTRA-GREEN SR castable. The castable was poured with an inside diameter of 8 in (203.2 mm) and surrounds the ten type B thermocouples that extend out through the access ports. The bottom section was poured with a cone shape in the middle to force the slag to fall into a cavity in the bottom section. Each section is sealed with a gasket and inswool in between the two sections of refractory. It has a blow off rupture disc for emergency situations. The flue gas flow is channeled through the exhaust nozzle of the reactor. The bottom section can be separated from the reactor to remove build up slag after a couple of days of operation.

The exhaust nozzle is at 90 degrees from the main section of the reactor to mitigate heat transfer from radiation, separate the exhaust gas from the slag, fit in the reactor room and be easily manufactured. It is refractory lined and has a port for the spray quench system to enter. The spray quench will cool the flue gas to an acceptable temperature for stainless steel 310 (1800 °F) at atmospheric pressure. The heat exchanger will further reduce the flue gas temperature to an acceptable temperature for electronically controlled valves (400 °F). The valves between the heat exchanger and the cyclone will be used to control the pressure in the



reactor and to bleed off the reactor pressure in emergency situations. There is also a capped pipe installed for future work, which enable CO<sub>2</sub> in the exhaust to be recycled. Dampers will control the flow through the cyclone separator. The cyclone will collect ash in a barrel, which can be removed after several days of operation. The room was modeled in CAD to make sure all of the components fit together. A to-scale model of most of the components can be seen in Figure 4-2. The exhaust system will be explained in detail in the following sections.

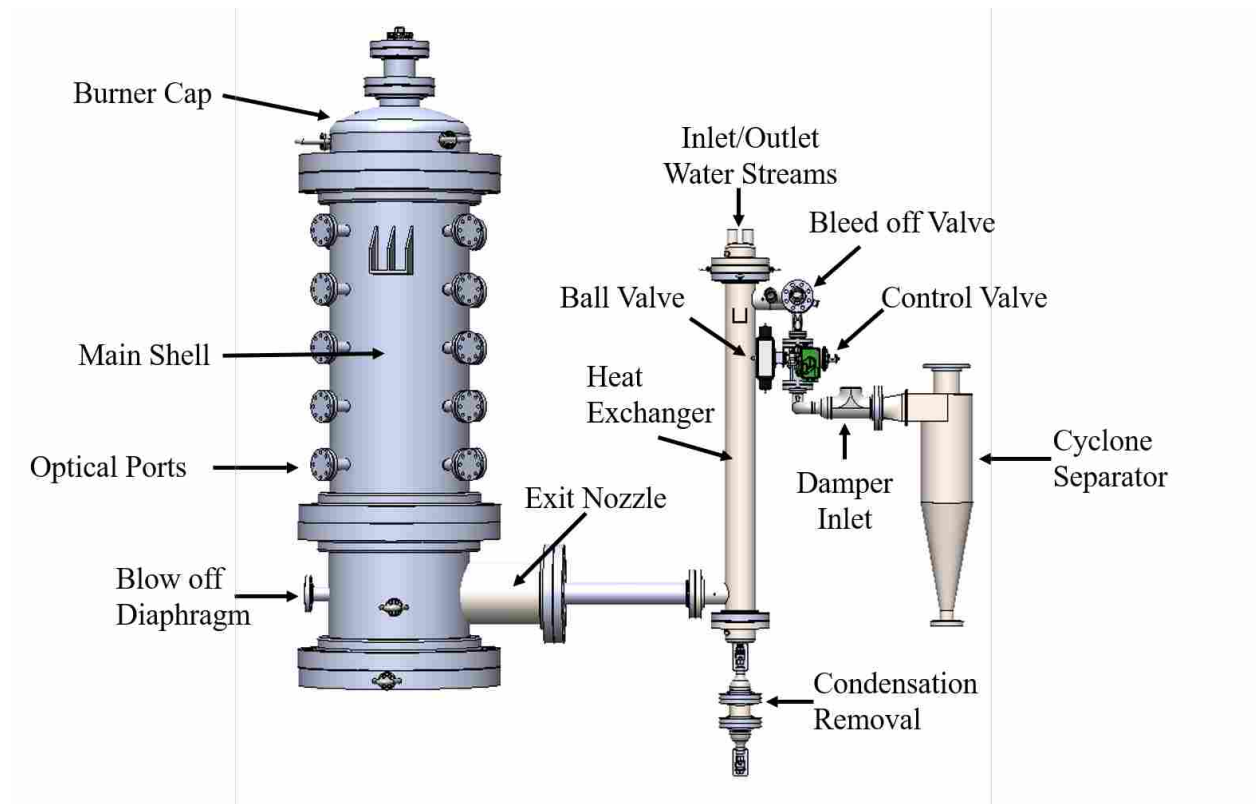


Figure 4-2: CAD drawing of the reactor in space.

## 4.2 Complete Exhaust System

A schematic drawing of the exhaust system is shown in Figure 4-3. Flue gas exits at the bottom of the reactor and into a refractory lined pipe containing the spray nozzle. Water is sprayed through a nozzle to cool the flue gas down to a safe temperature before entering the heat

exchanger. The one-pass shell and two-pass tube heat exchanger will transfer heat from the flue gas to the water flowing through 25 tubes. The coolant flow rate will be high enough so that the coolant will remain in the liquid phase and not become steam. The flue gas will go through two valves in parallel. The valves will be used to control the upstream pressure. The large valve will control flow at low pressure operation and the small valve at high pressure. Downstream of the valves the flow will be near atmospheric pressure. The heavy particulate in the flue gas will be separated by centrifugal force in the cyclone and fall through the bottom of the cyclone separator.

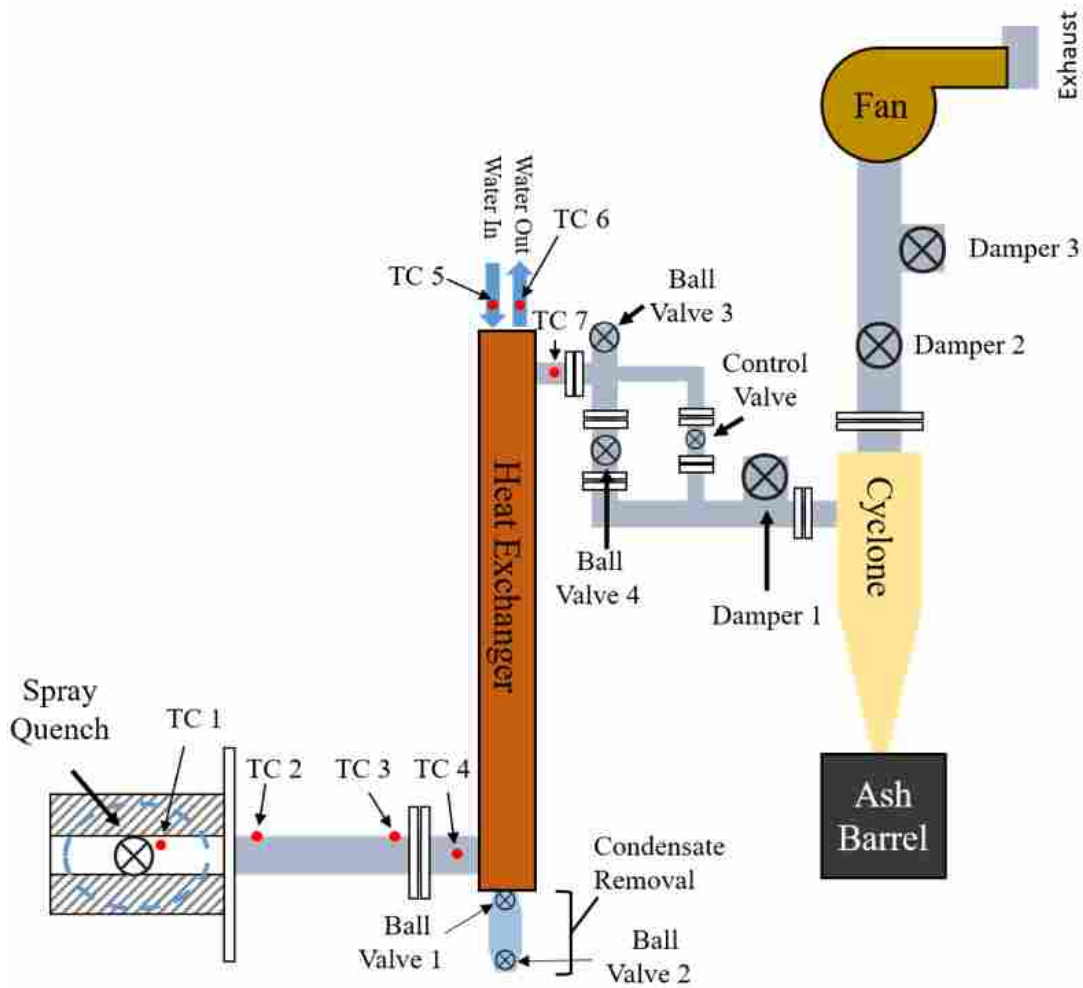


Figure 4-3: Schematic of exhaust system.

### **4.3 Reactor Exit**

The exit pipe of the reactor is a 12 inch (304.8 mm) diameter carbon steel schedule 80 pipe that is 18 inches (457.2 mm) long. It has 2-inch-thick insboard 2600 HD on the outside diameter followed by ULTRA-GREEN SR cement poured to an inside diameter of 3 inches. A 2 inch (101.6 mm) hole was cored out perpendicular to the flow to allow the spray nozzle to enter the flue gas stream.

### **4.4 Spray Quench System**

Figure 4-4 shows a schematic diagram of the spray system and components. The spray quench system was designed to cool the flue gas down to a temperature so that non-refractory lined surfaces could be used. The spray nozzle predicts that the flue gas flow of 309 lb/hr at a temperature of 3080 °F will require 75.4 lb/hr of water to vaporize to cool the mixture to 1800 °F. The spray nozzle selected for this flow rate is 13785-SS1.5 from Spraying Systems Co. The spray nozzle has a theoretical range from 0 to 99.2 lbs of water per hour, which is enough for the predicted needs. The water pump, CAT PUMPS model 4DX03ELR, can supply up to 165 lb/hr. A list of all of the component part numbers can be found in Appendix C.

Opto22 will be used to interface and control multiple components with the Programmable Automation Controller (PAC). The PAC will control the Variable Frequency drive (VFD) by sending it a 4-20 mA signal. The VFD will power the motor and control the motor speed. The motor speed controls the flow rate that is sprayed through the nozzle into the reactor. The Opto22 program will use Thermocouple 1 (TC 1) and surface TCs 2 and 3 shown in Figure 4-3 for feedback control to determine if the flow rate of water spray is high enough to cool the

exhaust gas to the desired temperature. The pressure and flow rate of water will also be recorded using Opto22. The correlation of flow rate to pressure can be seen in Figure 6-1. The nozzle sprays a fine mist into the reactor flue. A solenoid valve and one-way valve were added to control the flow of the system. The solenoid valve prevents water from flowing through the pump and into the reactor when the reactor pressure is below the water supply pressure. The one-way valve prevents flue gas from entering the pump when the reactor pressure is higher than the water supply pressure.

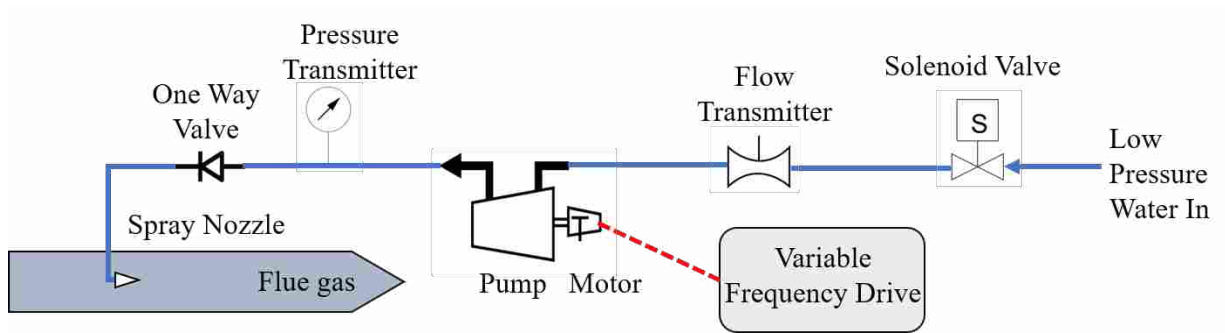


Figure 4-4: Schematic of spray quench system.

#### 4.5 Heat Exchanger

The heat exchanger is shown in Figure 4-3 downstream of the spray system. Two thermocouples TCs 4 and 7 are located at the inlet and outlet of heat exchanger to determine the amount of heat removed from the exhaust gas and to ensure that the heat exchanger is removing enough heat to safely operate the control valves which must function below 400 °F. TCs 5 and 6 measure the water inlet and outlet temperatures entering and leaving the heat exchanger. The outlet temperature TC 6 will be used to ensure that the water in the heat exchanger does not boil. TCs 4-7 can also be used to determine the overall efficiency of the heat exchanger.

The length of heat exchanger was calculated from the thermodynamic model presented in Chapter 3. The full details of the model are in Appendix A. The key parameters for the calculation are presented in Table 4-1. The model predicted that a length of 2.72 feet for the shell was needed to cool the flue gas from 1800 to 400 F (1255 to 477 K). Through weekly design reviews, it was decided that a factor of safety of two was needed for the length of the final design of the heat exchanger. A factor of safety is due to fouling and the corrosive environment that will be presented in normal operating conditions. The HX shell is made from 6 inch O.D. 5.76 I.D. schedule 80 stainless steel 316 pipe with a length of 6ft. The 6 inch diameter allowed the HX to be manufactured and modified without pressure vessel certification. The inside diameter of the pipe constraint led to several designs of tube sizes as well as tube bank configurations. A 3/8 inch, 316 stainless steel tube with a wall thickness of 0.065 inch was chosen because of its large surface area and the ability to be machined and welded with relative ease. The tube bank has 25 tubes. The configuration can be seen in Figure B-5-7 in Appendix B. All the CAD drawings for the HX can be seen in Appendix B.1.

Table 4-1: Effectiveness-NTU calculations.

variable	Imperial	S.I.	variable	Imperial	S.I.
$\epsilon$		0.77	$h_i$	528 Btu/h*ft <sup>2</sup> *°F	2998 W/m <sup>2</sup> *K
$C_{min}$	143 Btu/h*°F	75.46 W/K	$h_o$	45.91 Btu/h*ft <sup>2</sup> *°F	260.7 W/m <sup>2</sup> *K
$C_{max}$	232 Btu/h*°F	122.43 W/K	$R_{f,i}''$	0.0056 m <sup>2</sup> *K/W	0.001 m <sup>2</sup> *K/W
$C_R$		.0617	$R_{f,o}''$	.034 m <sup>2</sup> *K/W	.006 m <sup>2</sup> *K/W
$E$	1.51		$U$	14.67 Btu/h*ft <sup>2</sup> *°F	83.25 W/m <sup>2</sup> *K
$NTU$	1.59		$L$	2.72 ft	0.83 m

#### 4.5.1 Heat Exchanger Condensation Removal

At the base of the HX, a ball valve, pipe, and second ball valve are located for control and removal of condensation. Ball valve 1 opens for a short time allowing condensate in the HX to

flow into the pipe and then closes. Ball valve 2 then opens and vents the condensate into a tank at atmospheric pressure and then closes. The vessel between the two ball valves can hold 4.2 lb of water. The HX condensation removal can remove 75 lb/hr of water when cycled every 3 minutes. The components are schedule SS 316, schedule 40 and class 150.

#### **4.6 Pressure Bleed Valve**

Just downstream of the HX are a series of valves used to control pressure in the reactor. Ball valve 3 is a safety bleed off valve that will be used in emergency situations to depressurize the reactor. The valve is closed when activated during operation and is “fail open” or opens automatically when the power is shut off and will slowly bleed off the reactor’s flue gas through a 0.14 inch orifice. Discharge from full pressure is expected to take approximately 20 min. During typical high pressure operations the valve will be closed to enable the pressure in the reactor to build to 20 atm, but in an emergency situation or when the reactor loses power the valve may be opened to bleed out the system.

#### **4.7 Pressure Reduction**

Ball valve 4 and the control valve are used to control the pressure in the reactor. At atmospheric operating conditions both valves are open. Ball valve 4 closes in order to build pressure and the control valve uses a modulating orifice to control the flowrate and pressure of the upstream flue gas. The pressure reduces to atmospheric pressure after flue gas goes through the control valve. The fan pulls a vacuum and lets excess air enter through damper 1 to mix with the flue gas before it enters the cyclone separator. Damper 2 is inline in the cyclone exhaust duct and is used to control the pressure in exit flue gas. Damper 3 is used to help control the amount of excess room air that the cyclone separator can pull.

The control valve is a ½ inch modulating orifice. It is a badger valve model 1002GCN126SV04DEP36. The valve was sized for the flow rate and composition of the flue gas. Ball valve 4 is a 2 inch electrically actuated class 300 stainless steel ball valve. The CAD drawings and component lists are in Appendix B.2 and Appendix C.

## **4.8 Cyclone**

The cyclone was designed using the models presented in Chapter 3. The design was sent out for bids and Richard Sheet metal built it for \$2,200. A commercial cyclone would have cost \$9,000. The primary dimension  $D_o$ , which is the outside diameter of the main shell was designed to be 11 inches. The height of the cyclone is 44 inches. The inlet is 2.75x5.5 inches. The outlet is 5.5 inches. The bottom outlet to the ash barrel is 2.5 inches. . The CAD drawings are in Appendix B.3. The ducting from the cyclone separator to the atmosphere was also designed and installed.

### **4.8.1 Cyclone Efficiency**

Flue gas velocity and particle diameter are important parameters in calculating cyclone efficiencies. The velocity at the inlet of the cyclone was calculated to be 48.6 ft/s with excess air of 146.6 ft<sup>3</sup>/min from damper 1 and 136 ft<sup>3</sup>/min from the reactor flue gas. Table 4-2 shows the efficiency from block and mixed flow, which are two standard ways to measure efficiencies of a cyclone separator as explained in Section 3.3.4. It is projected that 99.01 % of the particles 10 µm and larger will be captured by the cyclone under mixed flow assumptions. The cut diameter, or diameter above which 50% of the particles will be captured was calculated to be 3.29 µm. The particles will be captured in the ash barrel.

Table 4-2: Cyclone efficiency.

Particle Diameter, $\mu$	$\eta_{\text{block}}$	$\eta_{\text{mixed}}$
0.1	0.00046	0.0005
1	0.04617	0.0451
2	0.18469	0.1686
3	0.41555	0.3400
3.29	0.50025	0.3936
4	0.73876	0.5223
4.65	1.00000	0.6321
5	-----	0.6847
6	-----	0.8103
7	-----	0.8959
8	-----	0.9479
9	-----	0.9762
10	-----	0.9901
15	-----	1.0000

#### 4.9 Transmittance Optical Set-up

The optical set up for the transmittance measurement is shown in Figure 4-5. It was designed with the ability to measure the soot volume fraction at each of the 5 optical ports on the reactor. The laser and power supply are mounted in a fixed location. The laser beam is directed by reflection off mirrors to line up with the center of a site port. The beam intensity is measured on the other side with a detector. The detector's signal is amplified and read into opto22 for analysis.



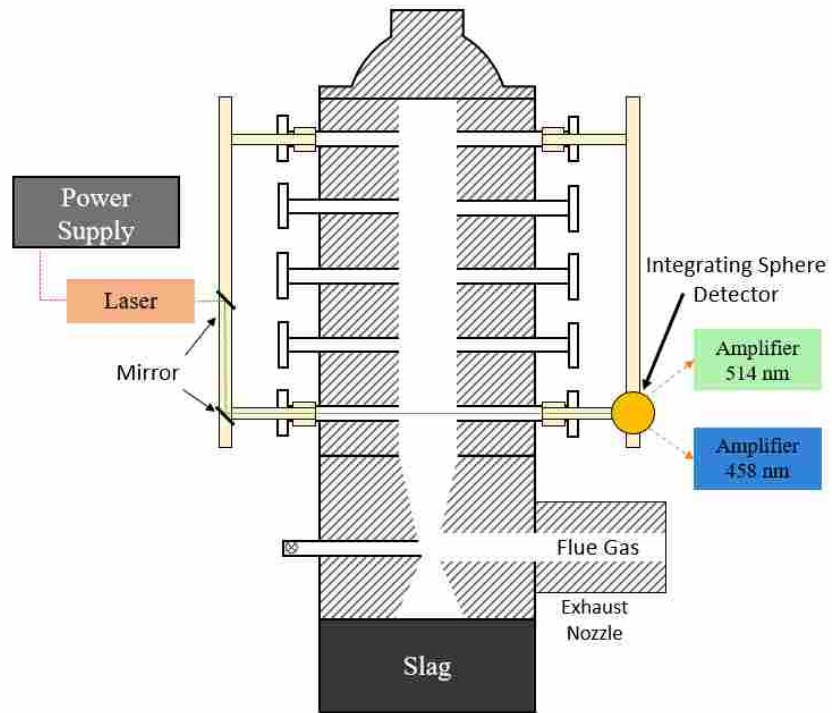


Figure 4-5: Schematic of POC reactor with laser mounts.

Figure 4-6 shows the specific design of how to mount each optical mirror with the use of pipe clamps, aluminum rails, rail mounts, post holders, post, mirror and a kinematic mirror mount. The CAD drawings and components are in Appendix B.4.

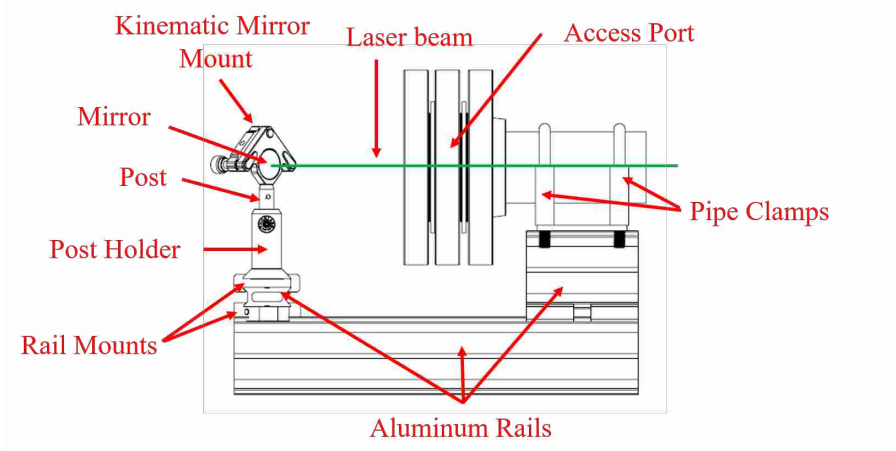


Figure 4-6: Schematic of laser port mount.

## **5 METHODS FOR TESTING**

The method for testing of the exhaust system and components of the POC proceed in the following steps.

- Component and subsystem testing
- Assembly and fit testing
- Air flow pressure and flow rate control testing (pre-combustion)

In this thesis each component refers to a specific part, i.e., 2 inch pipe, ball valve, slip on flange, etc. A subsystem refers to a group of components, i.e., heat exchanger, cyclone, condensate assembly, etc. The exhaust system refers to all the subsystems combined

### **5.1 Component and Subsystem Testing**

Each component that operates at pressure must be rated for at least class 300 for flanges and schedule 80 for pipes. The pressure parts include all the components in the heat exchanger, condensation assembly and piping up to ball valves 3 and 4 and the control valve (Figure 4-3). Each component must be welded or threaded and tightened to the specified torque in the exhaust system. Each subsystem that operates at pressure must be pressure tested before all the subsystems can be assembled in the exhaust system.

Electronic and pneumatic devices should be wired and tested. The appropriate gauge of wire should be run from the Opto22 Pac Control Modules to each specific device. Ball and

solenoid valves should be tested to confirm that they will open and close. Flow meters should read flow rates and thermocouples should read temperatures. Pressure transmitters should read pressures and send the signals back to Opto22. The variable frequency drive should control the motor's speed and the resultant pressure exiting the pump.

### **5.1.1 Spray Quench Flow Rate Test**

The method to test the flow rate of the spray quench is to first test each component with its operating conditions. The variable frequency drive should be able to operate with signals from 4-20 mA. The motor should be able to spin from 0 to 60 hz. The spray pump should be tested to spray water at flow rates from 0 to 99 lb/hr of water. The flow meter should read the flow rate exiting the spray nozzle. The solenoid valve should be able to open and close. Water lines should provide water from each component from the solenoid valve to the spray nozzle. To test the flow rate of the spray quench, the solenoid valve needs to be open. Then the variable frequency drive can be adjusted to the desired flow rate, which can be seen by feedback from the flow meter.

### **5.1.2 Pressure Component Tests**

Each component that operates at pressure must be pressure tested. The tests should be done on each subsystem. Each subsystem must be pressure tested individually by adding blind flanges or valves to stop flow at all inlets and outlets of a subsystem. An example would be to cap one side of a subsystem with a blind flange or a valve and to modify a 2 inch blind flange on the other side of the subsystem with two ¼ inch bungs (threaded on one side coupling) welded to the blind flange. The first ¼ inch line is for a pressure gauge and the second ¼ inch line is for a ¼ inch ball valve to allow water and CO<sub>2</sub> to enter. Water pressurized with CO<sub>2</sub> should be used to fill the piping in each subsystem. The vessel is first filled with water at atmospheric pressure.

Then, CO<sub>2</sub> is added from a tank with a regulator to increase the pressure to 20 atm. Then, the ¼ inch ball valve is closed and the subsystem can be tested at pressure for 30 minutes. The subsystem should not leak any drops of water or have a loss in pressure.

## **5.2 Assembly**

The assembly of the exhaust system should start at the reactor nozzle. The heat exchanger should be mounted and attached to the exit nozzle. Then the condensate assembly can be threaded to the bottom of the heat exchanger. The piping and valves from the heat exchanger to the cyclone should attach to the exit of the heat exchanger. The cyclone can be mounted and attached to the piping from the heat exchanger. Each flange should be tightened to the specified torque. Each pipe should be tight and secure. Once the exhaust system is mounted at a fixed location in the room, duct work and piping should be provided to the heat exchanger inlet, outlet, safety bleed off valve and cyclone vent. Sensors and valves should be wired and integrated into Opto22. All sensors should be tested to make sure they can be read. All valves should be tested to open, close, or modulate if that feature is available.

## **5.3 Air Flow Pressure and Flow Control Testing**

The reactor must be demonstrated to produce a negative pressure when running at atmospheric conditions. A negative pressure is wanted to keep the combustion gasses in the reactor, to have continuous flow, and to demonstrate that the exhaust fan is large enough to keep the product gases produced by the reactor from filling the room. The negative pressure can be tested by using the exhaust fan and opening an optical port to feel if air is flowing in or out. The mass flow controller of air can be used with the exhaust fan to see if a negative pressure is still

achieved. All three dampers should be tested concurrently with the exhaust fan and air mass flow controller to see how pressure changes with the modulating dampers.

## **6 RESULTS OF DESIGN TESTING**

This chapter reports on the testing done on the exhaust system to date, which includes quench spray results, cyclone efficiency model, subsystem pressure testing, assembly testing and atmospheric exhaust flow control. Testing to control the reactor pressure and hot exhaust gas testing has not yet been performed. This is due to delays in other reactor components and the development of a hazardous operating procedure (HAZOP).

### **6.1 Spray Quench Test**

The results of the spray quench test are shown in Figure 6-1. The graph shows an approximate linear correlation between flow rate and pressure between 40 and 66 lb/hr. This data was taken with the pump spraying into atmospheric pressure where the x-axis represents the gauge pressure or the pressure difference between the pump and the nozzle exit. In use, the nozzle exit will be at the reactor pressure or approximately 20 atm. or 294 psi. Subtracting 294 psi from the maximum pump pressure of 2000 psi gives the maximum pressure differential for the system. Using a best fit line through the existing data, the flow rate at a pressure differential of 1706 psi can be estimated with a flow rate 101 lb/hr of spray water. The model presented in Section 3.3.2 and Appendix A predicts that 75.4 lb/hr is needed to cool the flue gas from 3080 °F to 1800 °F. The current orifice was therefore measured to flow sufficient water to cool the

exhaust as needed. If larger flow rates of water are needed, a larger orifice can be used in place of the current orifice.



Figure 6-1: Pressure and flow rate correlation for the spray quench system.

## 6.2 Pressure Testing of the Exhaust System

The heat exchanger and heat exchanger to cyclone subsystems were each hydrostatic tested at 500 psi. All of the ports were capped except for one. That port allowed water and CO<sub>2</sub> to enter and measured pressure. The condensate collector was tested at 350 psi. There was no audible noise heard from any leaks. There were no drips of water observed. The condensate collector lost 10 psi in 30 minutes and the heat exchanger and heat exchanger to cyclone subsystem lost less than 1 psi.

### **6.3 Complete Assembly of the Exhaust System**

An image of the complete assembled exhaust system is shown in Figure 6-2. The exit nozzle is in the bottom left corner of the image and is the same grey color as the main reactor. The spray quench orifice is mounted in the top of this horizontal exit but cannot be seen in the image. The spray pump and variable frequency drive (shown in detail in Figure 6-3) are mounted on the back wall with stainless steel tubing connecting to the nozzle in the exit section. A large 12 inch flange reduced the diameter of the exit section to the 4 inch stainless steel pipe instrumented with thermocouples leading to the vertically mounted heat exchanger. Cooling water enters and exits the heat exchanger at the top as noted. The tubing in the heat exchanger (see Figure 6-4) can be removed for cleaning. The tubes can be cleaned with a pressure water and files to removed build up on the tubes. The condensation collector subassembly is at the bottom of the heat exchanger but cannot be seen in the image. An expanded view of this subsystem is shown in Figure 6-5. The subsystem of control valves and damper between the heat exchanger and cyclone are noted in Figure 6-2 with an expanded view shown in Figure 6-6. This subsystem leads into the vertically mounted cyclone as shown where the exhaust exits at the top of the cyclone and ash collects at the bottom in a barrel that can be periodically removed and emptied.

A SS 316 spiral wound flexitallic gasket is used between each flange. The specified amount of torque can be looked up in the flexitallic gaskets specifications. The schedule and class of each part can be found in Appendix B.



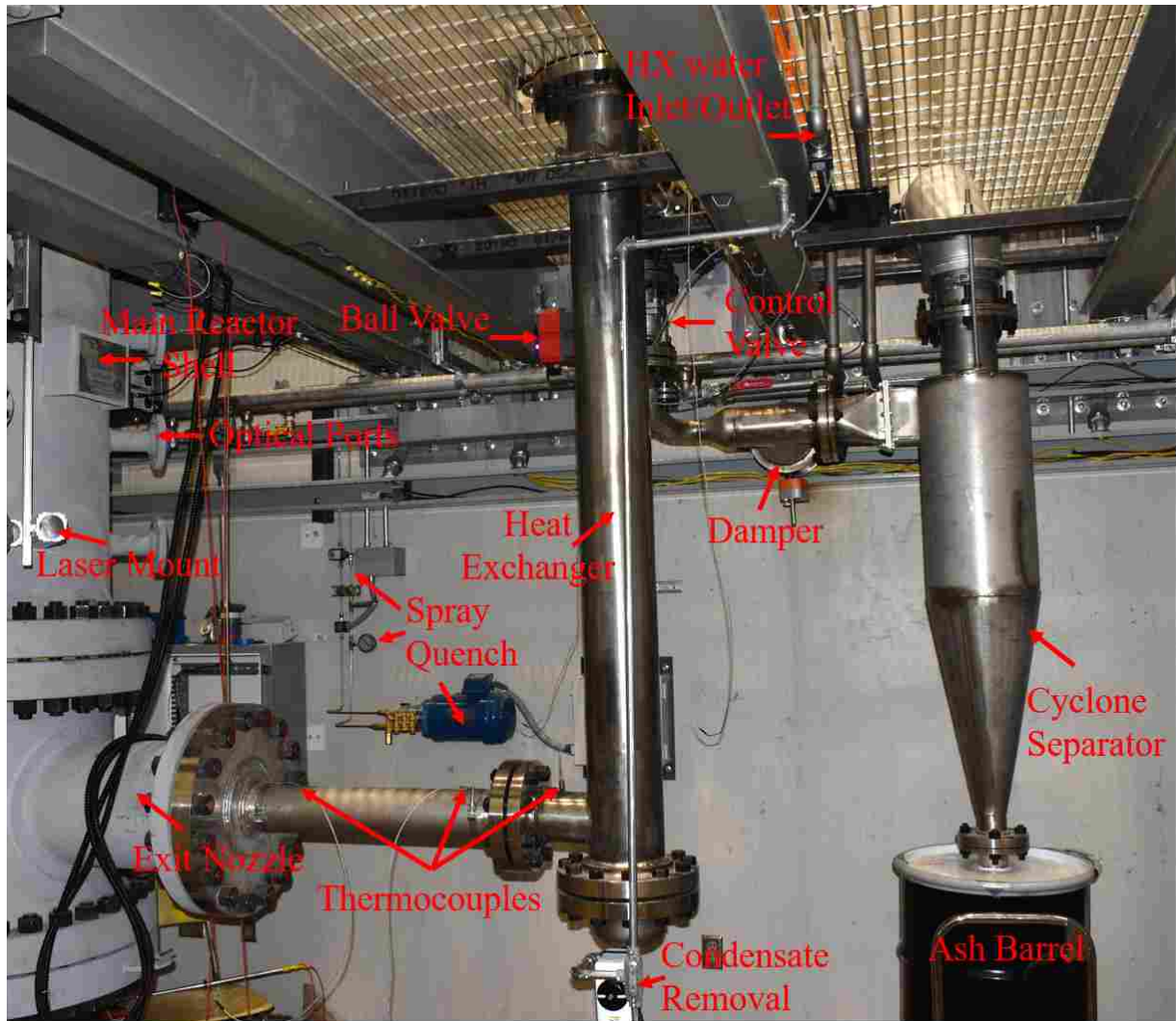


Figure 6-2: Assembled exhaust system.

Figure 6-3 shows how the variable frequency drive (VFD), motor, pump, valves and tubing are mounted on the wall. The tubing proceeds to the spray nozzle of the reactor. The spray quench system has visual pressure gauge to enable the operator to verify the pressure of the spray pump at the location without accessing Opto 22. The VFD is in a NEMA 4 box to prevent dust and protect the VFD from electrical failure.

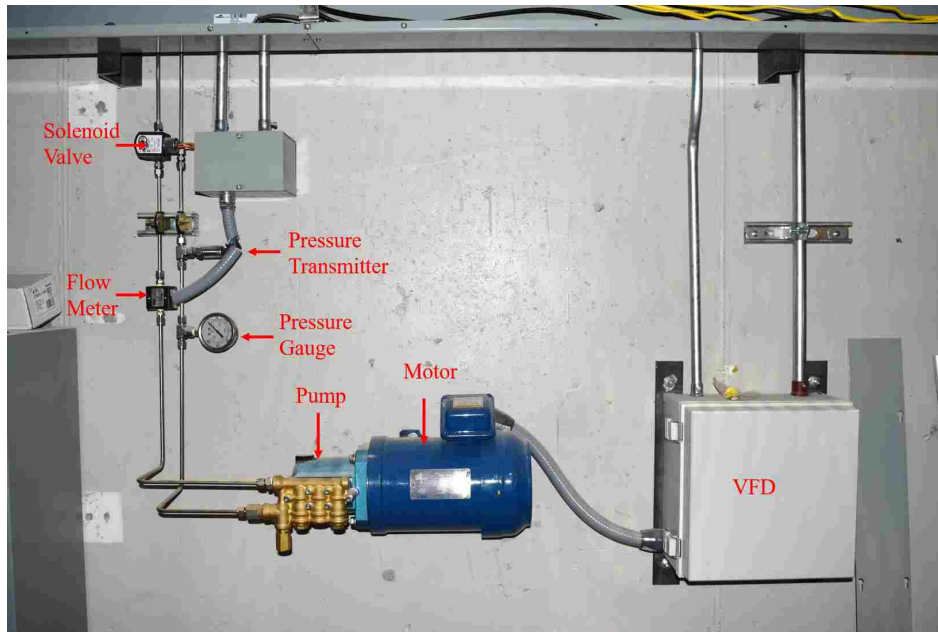


Figure 6-3: Spray quench assembly wall mount.

Figure 6-4 shows tube assembly for the heat exchanger. Twenty-five tubes were bent in a U shape and welded to a custom blind flange (See Figure B-5, B-6, B-7 in Appendix B.1). The tubes fit inside the shell (6 inch diameter by 6 ft. long shell) as shown in Figure 6-4.



Figure 6-4: Heat exchanger shell and tube design.

Figure 6-5 shows the condensation assembly. The two 2 inch ball valves are located above and below the collection pipe. The valves were tested and audibly observed to open and

close as programmed by Opto22, but the actual removal of condensate under pressure has not yet been tested.

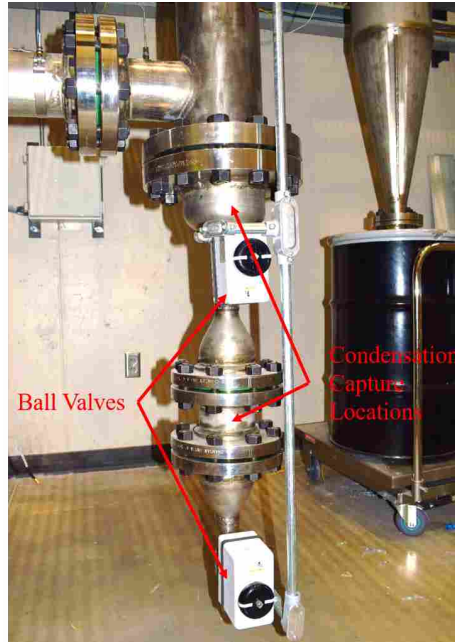


Figure 6-5: Condensation assembly

Figure 6-6 shows the piping and valves from the heat exchanger to the cyclone. The weight of this subsystem is supported by the heat exchanger connections. Upon exiting the heat exchanger the gas can take one of two paths. Normally it will turn and go vertically downward toward the ball valves and control valve. The 2 inch ball valve is open when the reactor operates at atmospheric pressure firing conditions, allowing flue gas to proceed without restriction. When closed, the flow must proceed through the control valve which restricts the flow and enables the upstream pressure to increase. The control valve, not yet delivered, will be located at the position shown.

Alternatively, exhaust gas can continue horizontally toward the CO<sub>2</sub> recycle valve and safety bleed off orifice. There is not currently a place for the CO<sub>2</sub> recycle to go and that path is

capped. The bleed off orifice is located within the triple flange. The first flange is a slip on flange that is welded on the 2 inch pipe. The second flange is a blind flange that has an orifice drilled out of it and the third flange is attached to the ball valve. The bleed off valve is closed during reactor operation but opens if the reactor loses power or any other condition is detected that requires the reactor to be emptied.

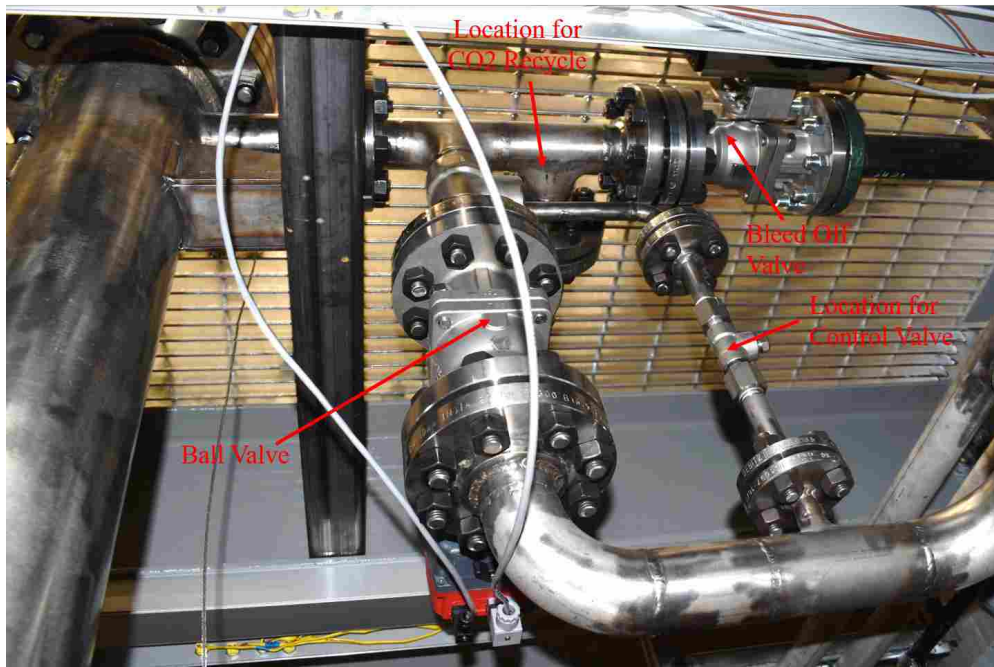


Figure 6-6: Heat exchanger to cyclone assembly.

Figure 6-7 shows the exhaust ductwork from the cyclone to the atmosphere. The ducting was installed above head level to provide room to work around the reactor. The two damper actuators were installed to control the amount vacuum pulled by the cyclone. The top damper allows excess room air to be brought into the vent. The bottom damper is in line with the exhaust flue gas and controls the flow directly by changing the pressure pulled by the vacuum.

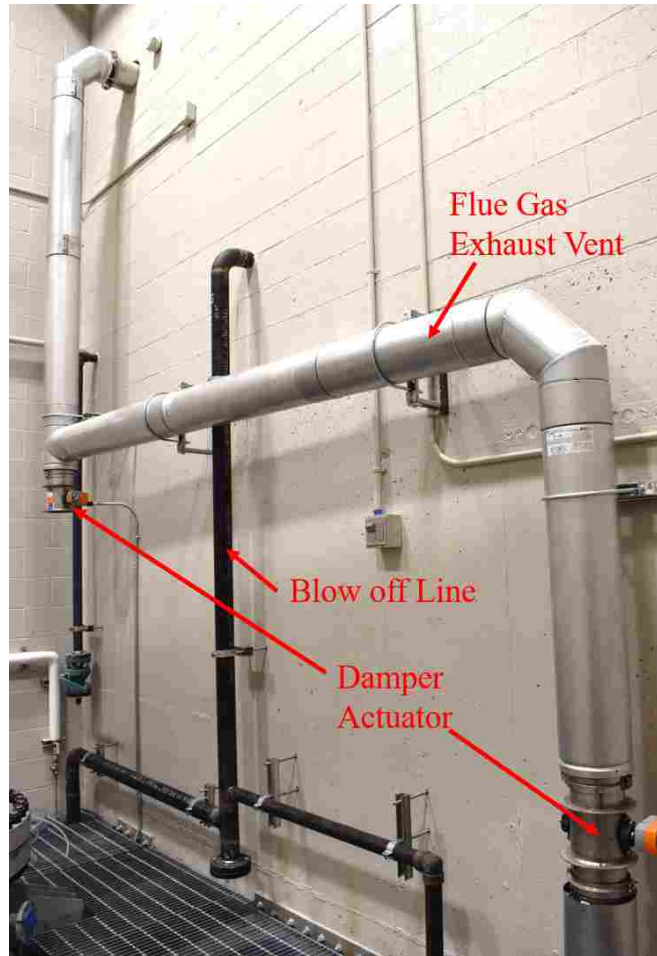


Figure 6-7: Cyclone exhaust vent to atmosphere.

Figure 6-8 shows the supports for the H600AL laser and the NLC 2270 argon-ion laser power supply. Additional mounts for the detectors and PDA200C amplifier are on the other side of the reactor. These mounts were built to be removable after testing for the two-color laser extinction method are done or another test is needed. The argon laser produces a laser from 458-514 nm at 100 mW. Two wavelengths of interest are separated by 458 and 514 nm filters. This produces two separate signals as if two separate lasers were used. Optical rail mounts are located at the bottom right hand side of the main reactor.

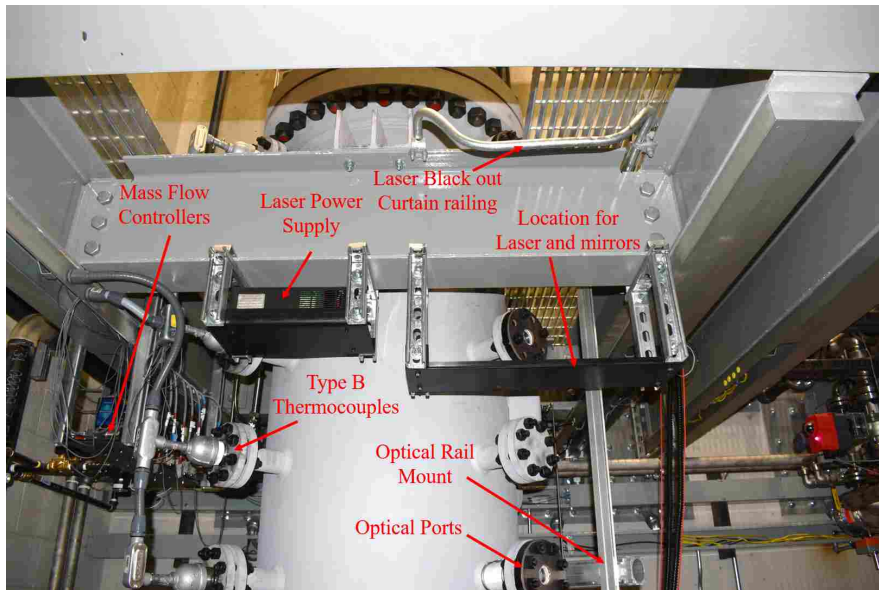


Figure 6-8: Laser support stands.

Figure 6-9 shows the safety black-out curtain designed to safely use the Class 3a laser. A laser mount railing is used to hold the curtain in place. The curtain is separated in three section to provide access to the laser, mounts, and mirrors located inside of it.

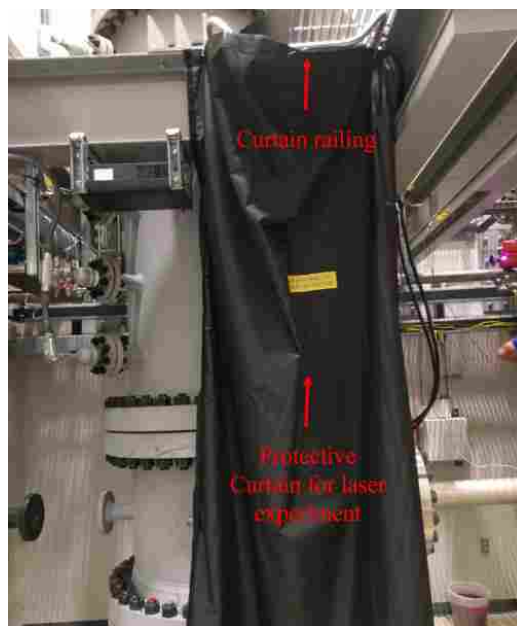


Figure 6-9: Laser protection curtain.

#### **6.4 Air Flow and Pressure Control Testing**

A test to determine if the exhaust fan was strong enough to overcome flow losses in the exhaust system was performed by opening and closing damper 1, 2 and 3 (Figure 4-3). Damper 2 is fail opened and is in line with the exhaust flue gas. Dampers 1 and 3 are fail closed and provide room air if desired. A blind flange from an optical port was removed. The exhaust fan was turned on and a vacuum could be seen with a plastic flap mounted at the exit of the access port with damper 1 and 3 closed with damper 2 opened. A negative pressure also occurred when damper 1 was opened. When dampers 1 and 3 were both opened, there was a small negative pressure on the optical port. When damper 2 was closed to about 50 percent with dampers 1 and 3 opened, there was no flow into the reactor through the optical port.

## 7 SUMMARY AND CONCLUSION

The exhaust system is an essential part of the pressurized oxy-coal reactor at Brigham Young University. The exhaust system has the capabilities to control the reactor pressure, cool the flue gas down to temperatures that allow the use of electronic valves, depressurize and separate particulate from the flue gas, and vent the flue gas to the atmosphere. Mathematical models were developed to determine the flow rates of water spray, the number and length of heat exchanger coils, and the efficiency of particle separation. The exhaust system was designed, fabricated and assembled to meet the design requirements and constraints given (Table 3-1). The first requirement was to cool the flue gas exiting the main reactor to temperatures that no longer required the outside shell material to be refractory lined. This was done with a spray quench. The model predicted that 75.4 lb/hr of water is needed to cool 309 lb/hr flue gas down from 3080 °F to 1800 °F. A pressure vs. flow rate curve was measured and used to estimate the flow of the spray as a function of water pressure. The second requirement was to cool the hot flue gas from the spray quench down to a temperature at which electronic valves can operate. A shell and tube heat exchanger was selected, designed and fabricated, to cool the flue gas from 1800 °F to 400 °F so that electronic valves could be used. A heat transfer model predicted that the heat exchanger with a diameter of 6 inches (0.15 m) and a length of 0.83 m was needed to cool the flue gas. A pipe with a length of 6 feet (1.82 m) was selected. The HX has a safety factor of 2 was due to fouling and the corrosive environment that will be present in normal operating conditions. The



third requirement was to remove excess condensation in the heat exchanger. A device with two ball valves was designed and manufactured to remove the condensation periodically. The fourth requirement was to provide a safety bleed off valve. The reactor was designed to release the flue gas from the reactor in 20 minutes at a pressure of 20 atm in emergency situations. A model predicted that an orifice of 0.14 inch was needed to relieve the pressure of the flue gas in the reactor. A ball valve was chosen, and an orifice was manufactured to accomplish this reduction in pressure. The fifth requirement was to control the pressure of the reactor from atmospheric to 20 atm. Two valves were sized and selected to reduce and control the pressure. The sixth requirement was to separate the particulate in the flue gas. Models were used to size and select a cyclone separator. A cyclone with a diameter of 11 inches was designed and manufactured to remove 99% of the particles greater than 10  $\mu\text{m}$ . The last requirement was to design mounts for a two-color laser extinction method. The design and set up allows measurements on all five optical ports.

The design and construction of the exhaust system was integrated with the overall reactor. The design was integrated with the reactor by using a CAD model of the reactor room that included the main reactor and I-beams in the room. The placement of the I-beams were used to know the size and shape available for the exhaust system. The designs of each subsystem were redesigned to fit in the space available in the room. Each component was welded or threaded together to form a group of components or subsystem. Then each subsystem that operated at pressure was tested at 20 atm. Each subsystem was attached to its adjoining subsystem to form the exhaust system that attached to the main reactor. Piping and ducting from the exhaust system to the water, air, vent, and safety line were manufactured. Wiring for valves, meters and thermocouples were wired into Opto22 control modules.

The reactor will be used for two-color extinction soot measurements, as well as other experiments that will document the physical processes occurring in oxy-coal combustion. The design and fabrication of the exhaust system has saved BYU thousands of dollars enabling the system to be fabricated within the DOE budget.

This work documents the exhaust system of the POC for the reference of future researchers. It is expected that they will reference this work to understand the function and components of the exhaust system. The document will facilitate operations, modifications and repairs to the POC.

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## APPENDIX A. THERMODYNAMIC CALCULATIONS

The spray system and heat exchanger energy balance calculations were done in Python using a thermodynamic property calculator program called Cantera. It was modeled as a shell and tube heat exchanger based on equation presented in Chapter 11 of Fundamentals of Heat and Mass Transfer by Bergman et al. [27]. The flue was modeled as CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, and N<sub>2</sub>. Spray water is used to cool the flue gas from 3080 F to 1800 F. The spray water was model to evaporate once it cooled down the flue gas. Raoult's law is used to calculate the amount of condensation in the heat exchanger. The length of the heat exchanger was calculated with a factor of safety.



```

H      cG hG      kW hV
H      H      kW hvsp_h2o
h      H (mG      mG)
Y      (mG pd      kW yW)      (mG      kW)
gas_HPY      h, Pr, Y
Twant      Tfe

```

```

c = gas_T - Twant

```

```

mkguess
mX      fsolve(F, mkguess), []

cph      gas_cp, mass
mT      mG      kW

mT = (
    mT,      ,      )
mT = (
    mT,      ,      )
mT = (
    mT,      )
mT      ,gas mass_fraction_dict()
mT      ,gas mole_fraction_dict()

```

the flowrate of spray water is 34.214471705 kg/hr 8.89197626433 gal/hr

the volumetric rate of spray water is 373.190766175 mL/min

the total flowrate of the mixture is 174.21144717 kg/hr

```

case {'CO2': 0.7497210249247012, 'H2O': 0.250663755170729, 'N2': 0.0025211962083170987, 'O2':
mole {'CO2': 0.5592344674308127, 'H2O': 0.4292126293618898, 'N2': 0.002954494717656349, 'O2':

```

### 0.3.2 Find the amount of Condensation in the Heat Exchanger

```

In [3]: gas_hx      = Solution(
    T1

Pr

gas_hx_TPY      = T1, Pr, gas_Y

A
B
C
D
E
I      = T1
P      = np.exp(A - B / T - C / np.log(T) - D / T - E)

```





#### 0.0.4 Find the composition in the cyclone with the excess air

```

In [5]: gas_a = ct.Solution('air', T=300, P=1)

h_h2 = gas_cyc.enthalpy_mass
Pc

gas_cyc.HPY = h_h2, Pc, Y
b = gas_cyc.density_mass
Qt = mt_ac * b

gas_a.HPY = T, Pc, Y
a = gas_a.density_mass
Qt =
Qt =
Qa = Qt * Qb
ma = a * Qa

ha = gas_a.enthalpy_mass
hb = gas.enthalpy_mass
he = gas_ex.enthalpy_mass

mT = ma * mt_ac
h_final = (Qa * ma * ha + mt_ac * (mt_ac * ma))
gas_final = ct.Solution('air', T=h_final, P=Pc)
gas_final.HPY = h_final, Pc, gas_cyc.Y * mt_ac / gas_a.Y * ma
v_cyc = mT / (gas_final.density_mass * (
    (
        (
            (b, )
        )
        (
            (mt_ac, )
        )
        (
            (Qb, )
        )
        (
            (Qa, )
        )
    )
    , gas_cyc.T, , gas_cyc.T
    , gas_final.T, , gas_final.T
    , v_cyc, )

```

The density of the gas is 0.7258190500462868 kg/m<sup>3</sup>

The mdot of the gas is 167.77219796 kg/hr

The Volumetric flow rate of the gas is 231.148795212 m<sup>3</sup>/hr

The Volumetric flow rate of the air is 349.551204758 m<sup>3</sup>/hr

The Temperature after the pressure drop is 477.594 K ( 399.99919999999999 F)

The final Temperature before the cyclone is 336.7690888315385 K ( 146.51435829676933 F)

The velocity going through the cyclone is 14.8199312888 m/s

0.1 Now that the gas composition is know calculate the length needed for the HX

0.1.1 Find the heat transfer rate and the cooling water outlet Temperature

```

In [10]: R
         Di
         Do
         Dh      Do Di
         ratio   Di Do
         m       ml
         mc

         gas_ave      or Solution(
         gas_ave TPX  (Tr Tf) , Pr, gas X

         A_HX        (
         up pi      up pi )

         ve_HX       m (gas, hx density, mass A_HX)
         vi_HX       m (gas density, mass A_HX)

         v_ave       gas, ave density, mass
         v_ave       m (_ave A_HX)

         q           m (m1 ue)

         w           at Solution(
         Pw          , Pr, w )
         w TP       Te , Pe

         cpc        w cp_mass
         hci        w enthalpy mass
         hce        hci q mc

         w HP       hce , Pr
         Tco        w T

         v_ave      (
         v_ave      , v_ave,
         v_ave      , Tco, Tco
         v_ave      , mc, )

```

The heat transfer rate is 53195.9488248 J

The average velocity in the HX is 0.554246480667 m/s

The water outlet Temperature of the EX 336.23956061726 K (145.5612999831068 F)  
at a flow rate of 0.292 kg/s

## 0.1.2 Find $h_o$ for the cooling tubes

In [7]:

```

St =
D
Sl
chart = St/Sl

Vmax = St*(Dt/D) v_ave
mu_ave = gas_ave.viscosity
nu_ave = mu_ave/rho_ave
cp_ave = gas_ave.cp_mass
k_ave = gas_ave.thermal_conductivity

Prh = cp_ave*mu_ave/k_ave
ReDh = Vmax*Dh/mu_ave

c1 = chart
sl =
c2

Tsur = (Tco Tf)
gas_sur = c1.Solution( , , )
gas_sur.TPX = Tsur, Pr, gas X

rho_sur = gas_sur.density_mass
mu_sur = gas_sur.viscosity
nu_sur = mu_sur/rho_sur
cp_sur = gas_sur.cp_mass
k_sur = gas_sur.thermal_conductivity

Prhs = cp_sur*mu_sur/k_sur

NuDh = c2*c1*ReDh**0.41*Prh**0.33*(Prh/Prns)**0.25
ho = NuDh*k_ave/Dh

Tw_ave = (Tco Ts)

A
B
C
D
E Tw_ave
EE = A-E-1-C-T**0.25-D-T

```

```

A
B
C
D
E
T = Tw_ave
W = up * exp(A * B * T * C * up * log(T) * D * T * E)

w_ave = get SolutionX ( , )

Pz
w_ave TP = Ts , Pw

cp_ave = w_ave * cp_marr

Prx = cp_ave * kK

ReD = ac * C * (up * pi * Di * K)
NuD = ReD * ( ) * Prx * ( )

hi = NuD * W * Di

ks
Rfi
Rfi
Rfi
Rfi
Rfi

U = (Do * (Di * hi) * Rfi * Do * Di * Do * up * log(Do * Di) * ( ks) * Rfo * ho)

U3 = (Di * hi * ho) * (Di * hi * Do * ho)
Rd = U * U3
U4 = ( , Tw_ave, )
U5 = ( , ho, )
U6 = ( , hi, )
U7 = ( , U, )
U8 = ( , U3, )
U9 = ( , Rd, )

```

The water average is 314.619730300865 F  
 The fine gas heat transfer coefficient is ho= 264.141981591 W/m<sup>2</sup>\*K  
 The pipe water heat transfer coefficient is hi= 2964.26260535 W/m<sup>2</sup>\*K  
 The overall heat transfer coefficient is 83.5564192959 W/m<sup>2</sup>\*K  
 The overall heat transfer coefficient is of a clean RX 232.439238028 W/m<sup>2</sup>\*K  
 Fouling factor = 0.0076657617762 m<sup>2</sup>\*K/W

### 0.1.3 Find the Length of the HX

```
In [8]: De
        Te1 = Ta
        Thi = Tfa

        Cmin = m * cph
        Cmax = mc * cpc
        Cr = Cmin / Cmax

        qmax = Cmin * (Thi - Te1)

        q = qmax

        E = (1 - Cr) / (1 + Cr)
        NTU = (1 - Cr) / (1 - E) * np.log((E - 1) / (E - Cr))
        L = NTU * Cmin / (U * pi * Dc)

        print('Cr =', Cr, 'E =', E, 'NTU =', NTU)
        print('L =', L)

Cr is 0.001735402829 , E is 0.731204124562 and NTU is 1.86496342357
The length is 0.925995273213 m.
```

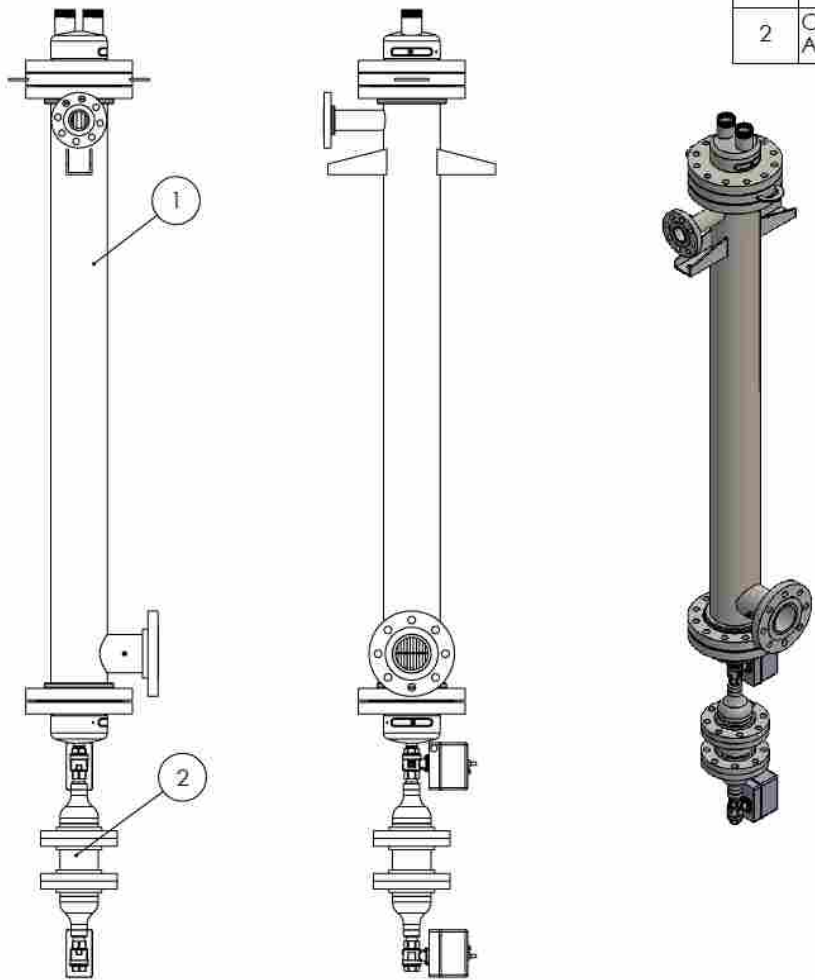
## **APPENDIX B. CAD DRAWINGS**

This appendix contains the Pressurized oxy-coal reactor (POC) CAD drawings of the exhaust system. The POC CAD drawings consist of the heat exchanger, heat exchanger to the cyclone, cyclone and laser mount. A SS 316 spiral wound flexitallic gasket is used between each flange. The specified amount of torque can be looked up in the flexitallic gaskets specifications.

## **B.1 Heat Exchanger CAD Drawings**

The heat exchanger was designed to remove heat from the flue gas at a temperature of 1800 °F to 400 °F. The heat exchanger was also designed to remove condensation build up. Two ball valves are used to periodically drain the condensation. All the components for the heat exchanger were manufactured in house.





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	HX Assembly	6 in shell and tube heat exchanger	1
2	Condensation Assembly	two ball valve condensation removal	1

DATE		MADE BY	
2/18/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
HX with Condensation Assembly			
SIZE A	DWG. NO. 1	SCALE 1:32	REV. A
CAD FILE: HX with Condensation Assembly			SHEET 1 of 10

Figure B-1: Drawing of heat exchanger with condensation assembly.

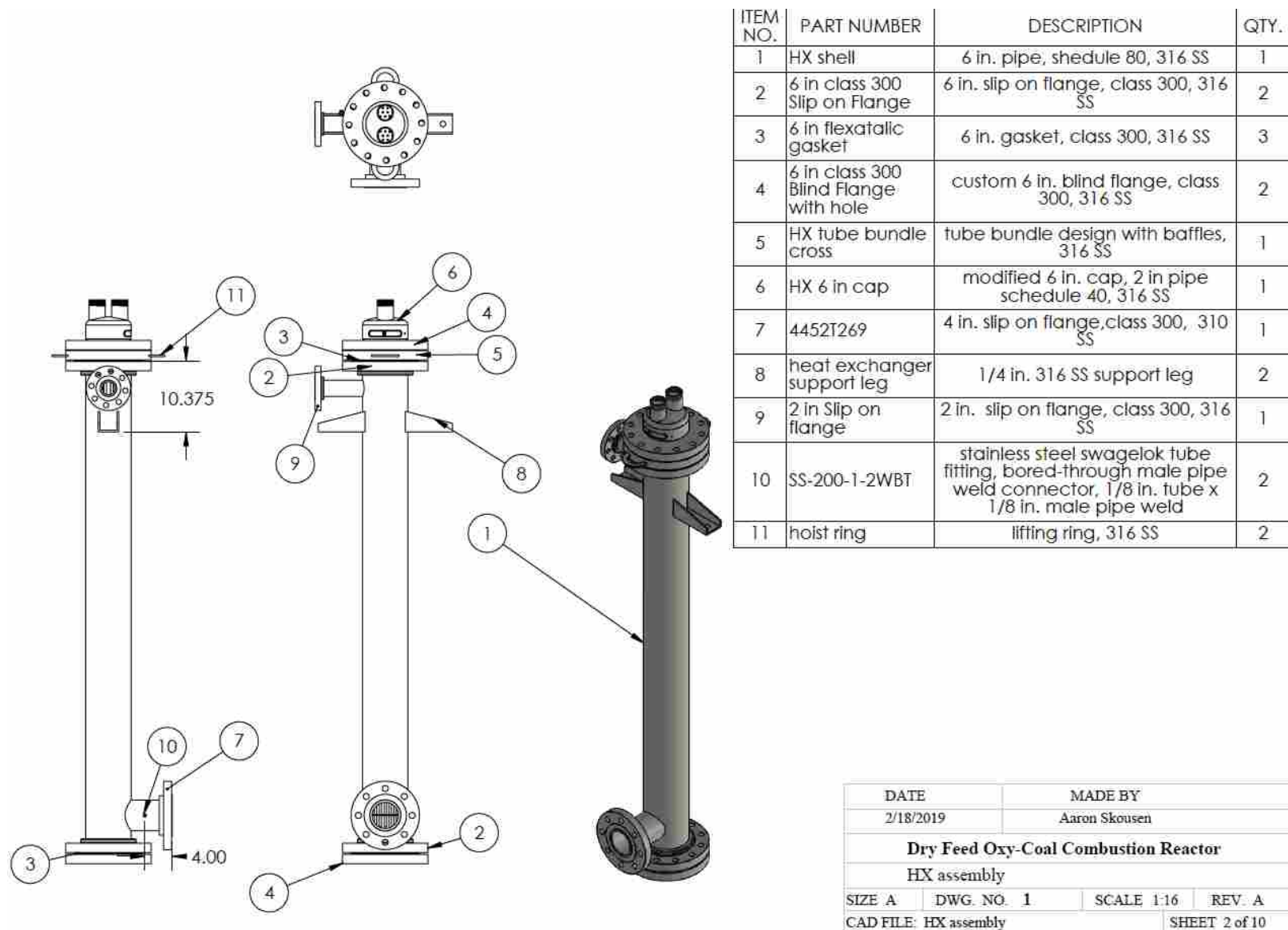
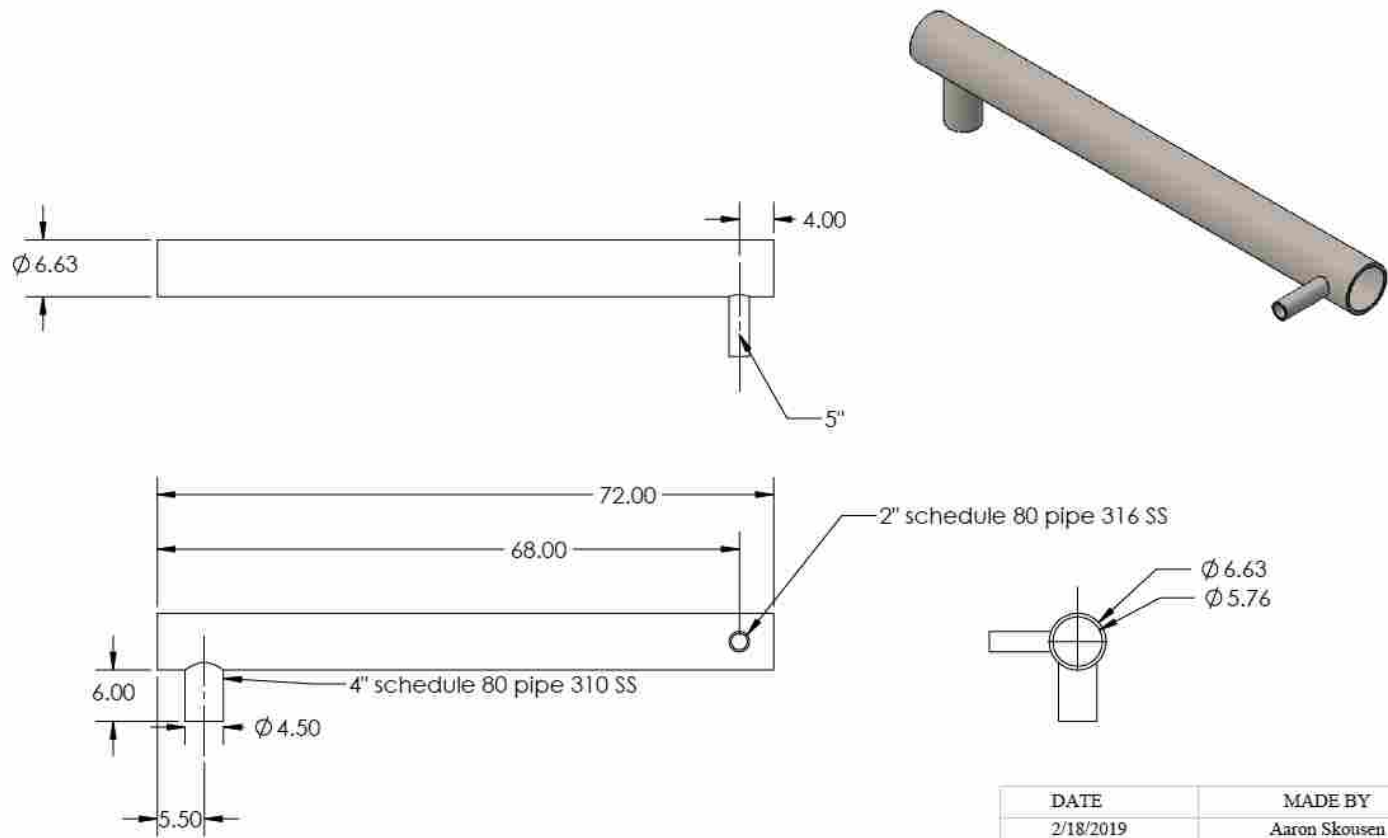


Figure B-2: Drawing of heat exchanger assembly.

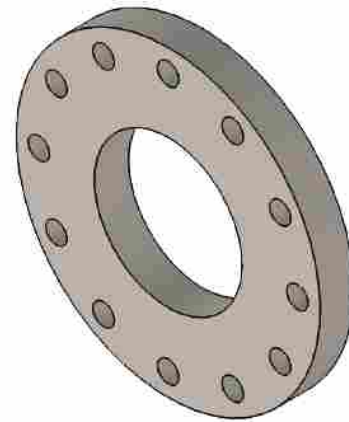
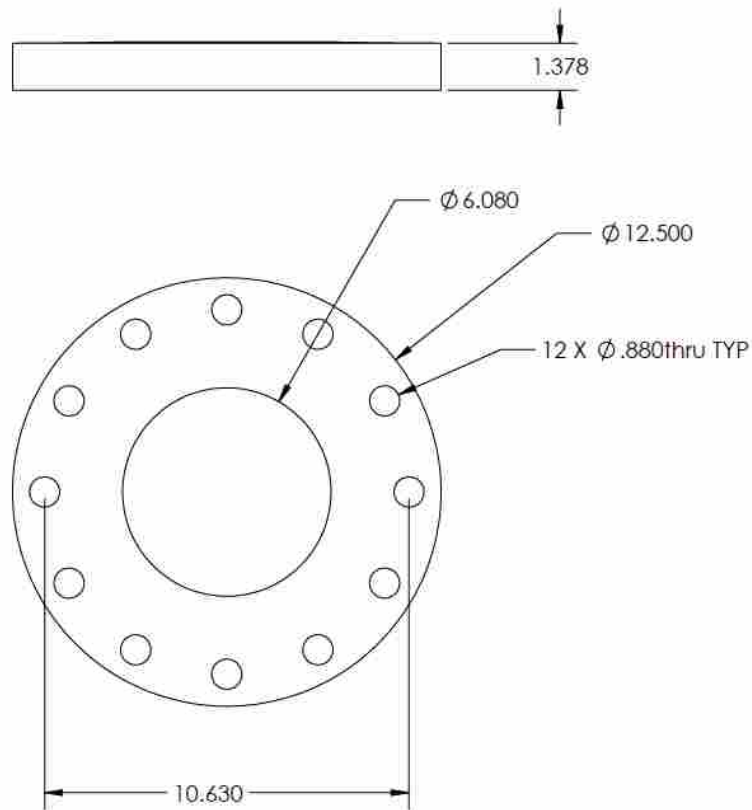
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	HX shell	6 in. pipe, shedule 80, 316 SS	1



DATE		MADE BY	
2/18/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
HX shell			
SIZE A	DWG. NO. 1	SCALE 1:16	REV. A
CAD FILE: HX shell			SHEET 3 of 10

Figure B-3: Drawing of heat exchanger shell.

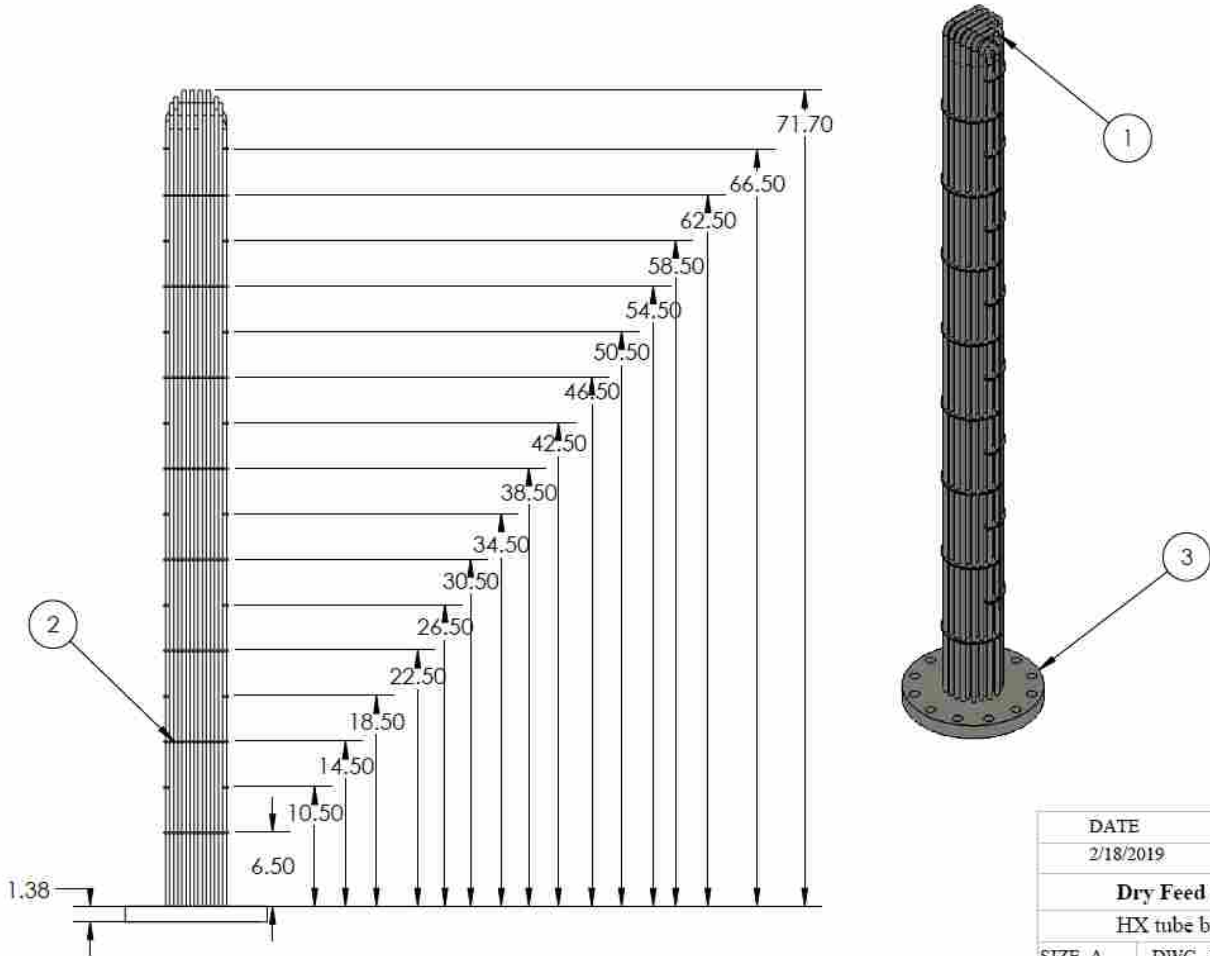
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
4	6 in class 300 Blind Flange with hole	custom 6 in. blind flange, class 300, 316 SS	1



DATE	MADE BY		
2/18/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
6 in class 300 Blind Flange with hole			
SIZE A	DWG. NO. 4	SCALE 1:4	REV. A
CAD FILE: 6 in class 300 Blind Flange with hole		SHEET 4 of 10	

Figure B-4: Drawing of custom blind flange for the heat exchanger top and bottom.

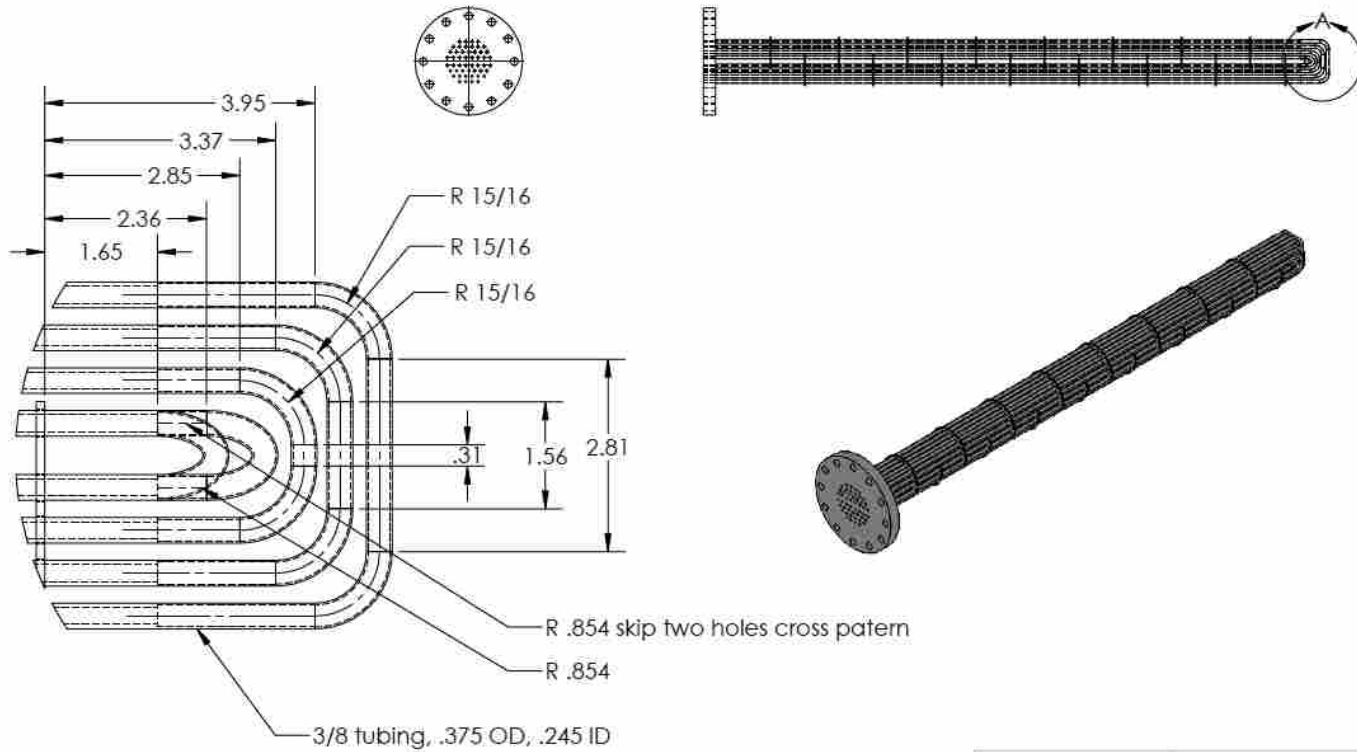
ITEM NO.	Part Number	DESCRIPTION	QTY.
2-1	1	Tubes	25
2-2	2	Baffles	16
2-3	3	Tube Bundle design	1



DATE	MADE BY		
2/18/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
HX tube bundle cross			
SIZE A	DWG. NO. 5	SCALE 1:16	REV. A
CAD FILE: HX tube bundle cross			SHEET 5 of 10

Figure B-5: Drawing of heat exchanger tube assembly.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
2-1	tubes	Tube bundle design and baffles 316 SS	25



DETAIL A  
SCALE 1 : 2

DATE	MADE BY		
2/18/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
HX tube bundle cross			
SIZE A	DWG. NO. 2-1	SCALE 1:16	REV. A
CAD FILE: HX tube bundle cross			SHEET 6 of 10

Figure B-6: Drawing of tube pattern in the heat exchanger.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
2-2	baffles	316 SS	16

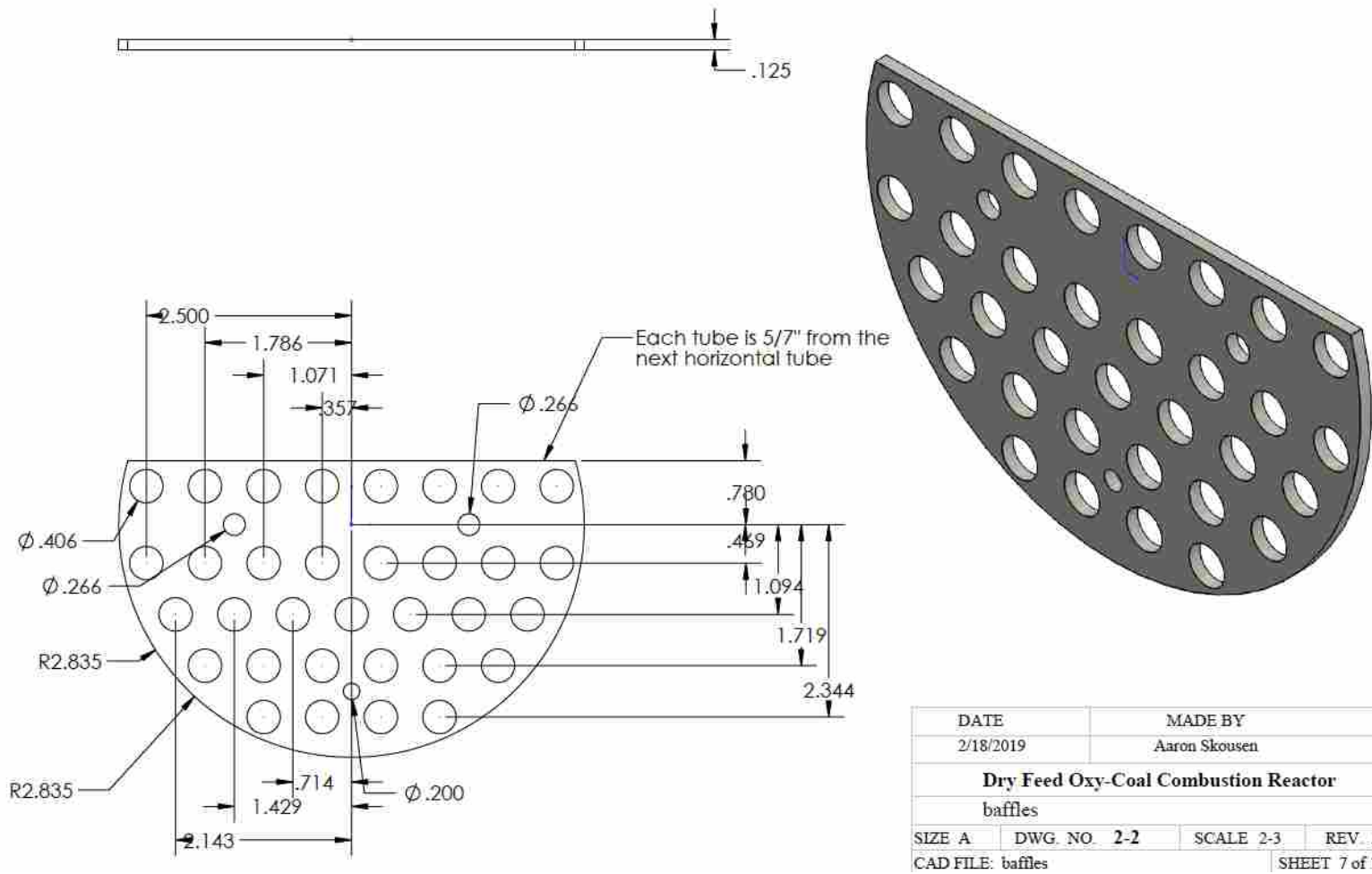


Figure B-7: Drawing of baffles in heat exchanger.

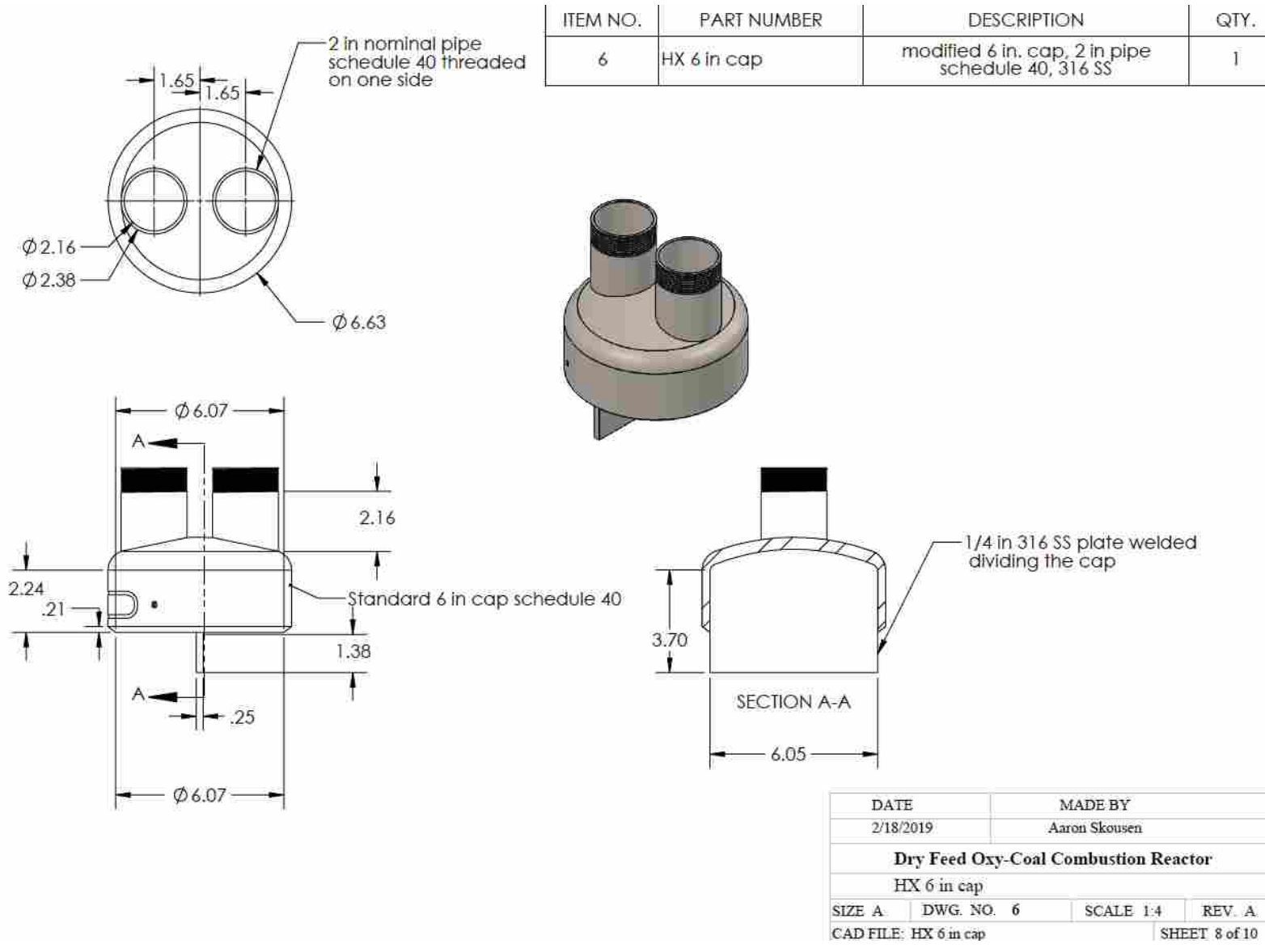
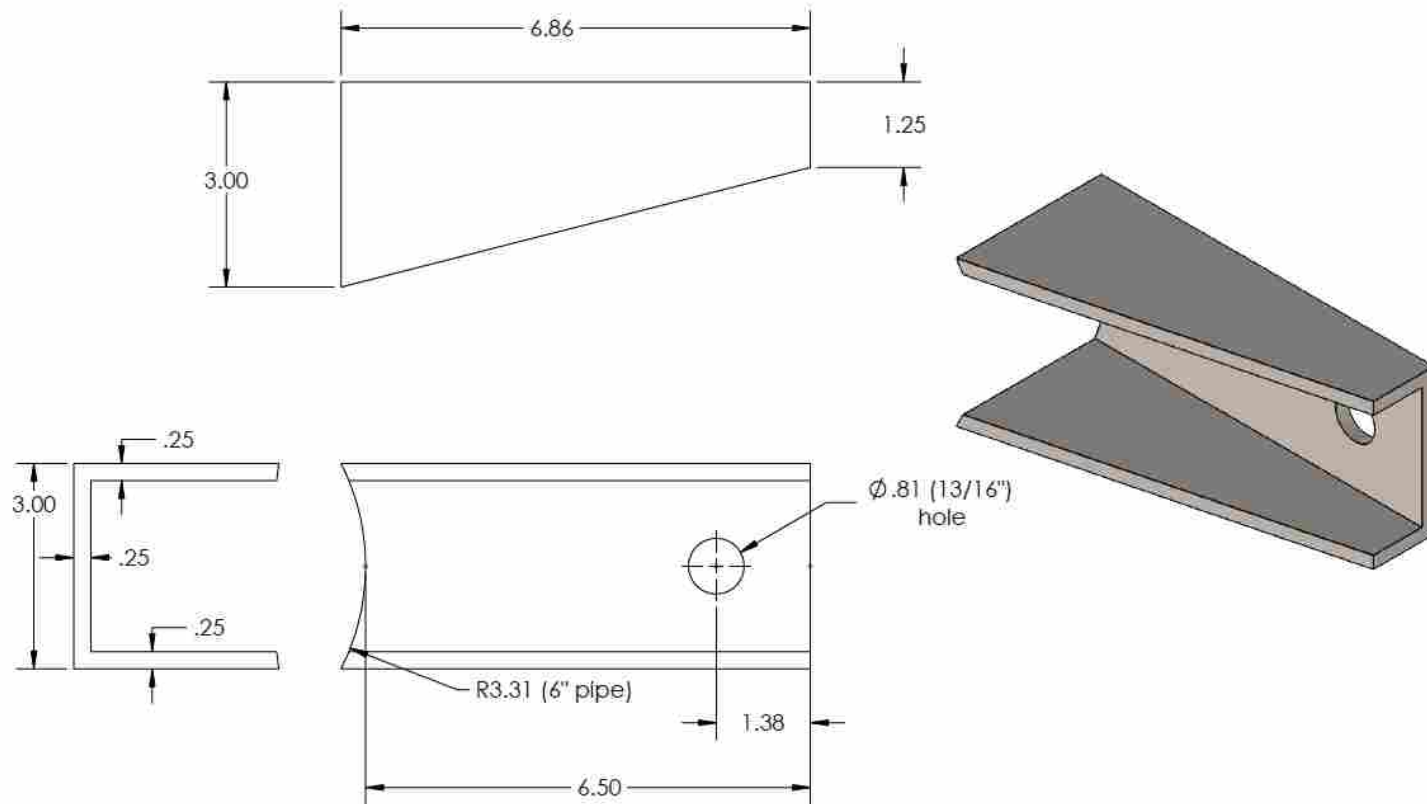


Figure B-8: Drawing of cap that divides the water in and out in the heat exchanger.

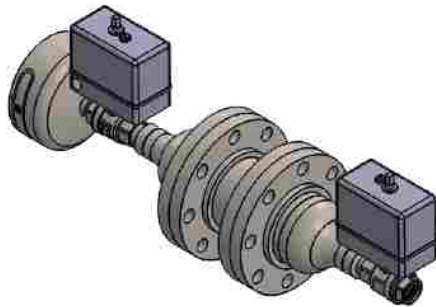


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
10	heat exchanger support leg	1/4 in. 316 SS support leg	1

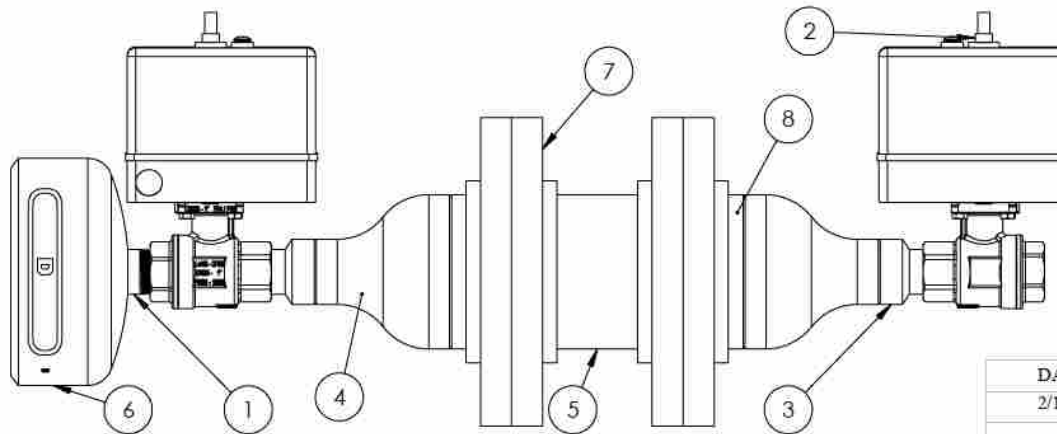


DATE		MADE BY	
2/18/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
heat exchanger support leg			
SIZE A	DWG. NO. 10	SCALE 1:2	REV. A
CAD FILE: heat exchanger support leg			SHEET 9 of 10

Figure B-9: Drawing for the support leg for the heat exchanger.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	9110T25	1 in. pipe thrd one end pipe nipple 316 ss, length 1.5 in.	1
2	2in ball valve	2in. electric actuated ball valve	2
3	9110T25	1 in. to 1.5 in. concentric reducer, schedule 40, 316 SS	2
4	43645K143	4 in. to 1.5 in. concentric reducer schedule, 40 316L SS	2
5	4in sch 40 pipe 4.5in length	4 in. sch 40 pipe, 4.5 in. length	1
6	HX 6 in cap to condensate	modified 6 in. cap, schedule 40, 316 SS	1
7	4 in, #150 slip on ff flange	4 in slip on flange, class 150, 316 SS	4
8	4 in pipe sch 40	4 in pipe sch 40, 1.75 in. length	2

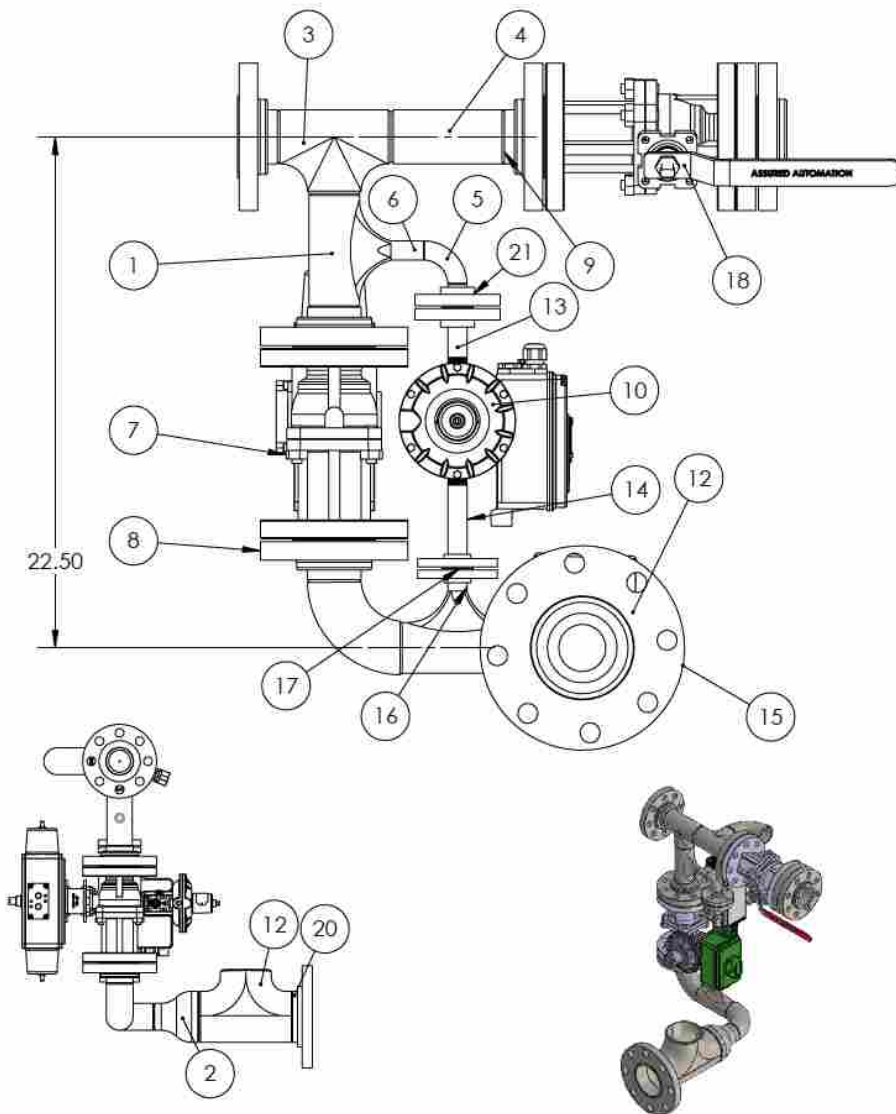


DATE		MADE BY	
2/18/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
Condensation Assembly			
SIZE A	DWG. NO. 2	SCALE 1:3	REV. A
CAD FILE: Condensation Assembly			SHEET 10 of 10

Figure B-10: Drawing for the condensation removal for the heat exchanger.

## **B.2 Heat Exchanger to Cyclone CAD Drawings**

The room requirements and installed I-beams influence the design from the heat exchanger to the cyclone components. A ball valve and a control valve were used to control the flow and pressure for the POC. When the POC is run at atmospheric conditions, both valves are opened. When the POC is run at pressure the ball valve is closed and the control valve changes the size of the orifice to regulate the pressure of the flue gas. All the components were assembled and welded in house.



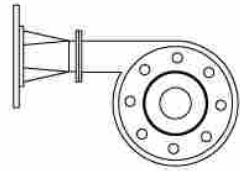
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1741K22	2" to .5" tee sch 80	2
2	45555K122	4" to 2" conc red sch 80	1
3	1741K22	2" tee sch 80	2
4	1741K13	2" 90 deg elbow sch 80	2
5	45555K511	.5" 90 deg elbow sch 80	1
6	45725K811	.5" pipe sch 80	1
7	2 in ball valve	air driven ball valve	1
8	2in slipon flange	2" slip on flange 300#	5
9	2 in pipe sch 80	2" pipe sch 80	4
10	.25 in control valve	.25" control valve	1
11	48805K44	.5" to .25 str red	2
12	45555K633	2" by 4" by 4" tee sch 40	1
13	9157K43	.5" pipe thr one side	1
14	9157K43	.5" pipe thr one side	1
15	4" flange	4" slip on flange 125#	1
16	4815T131	.5" pipe sch 80	2
17	44695K168	.5" slip on flange 150#	2
18	2 in manual ball valve	2" ball valve	1
19	4452T291	2" blind flange with 1/8" hole	1
20	4 in pipe sch 40	4" pipe sch 40	1
21	4452T261	.5" slip on flange 300#	2
22	45555K516	2" 90 deg elbow sch 40	1

DATE		MADE BY	
2/19/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
HX to cyclone Assembly			
SIZE A	DWG. NO. 1	SCALE 1:16	REV. A
CAD FILE: HX to cyclone Assembly			SHEET 1 of 1

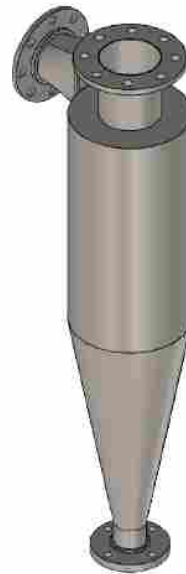
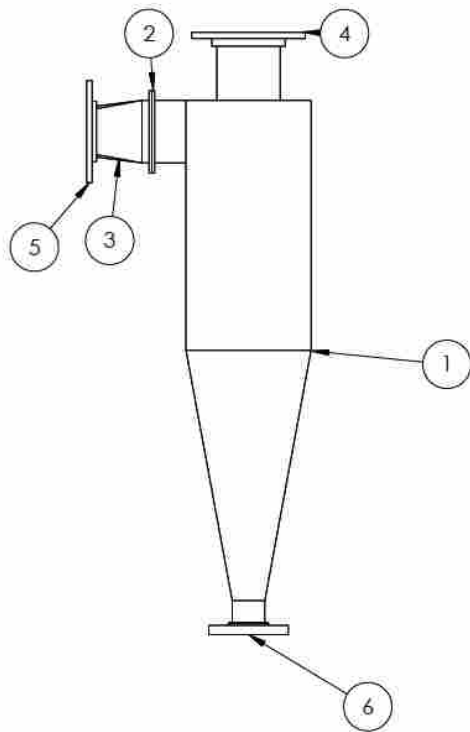
Figure B-11: Drawing of flue gas exhaust from the heat exchanger to the cyclone.

### **B.3 Cyclone CAD Drawings**

The cyclone separator was designed to have a flow rate of 17,000 cfm and remove 99% of all particles larger than 10  $\mu\text{m}$ . The cyclone was designed and then sent out for bids and manufactured by Richards.

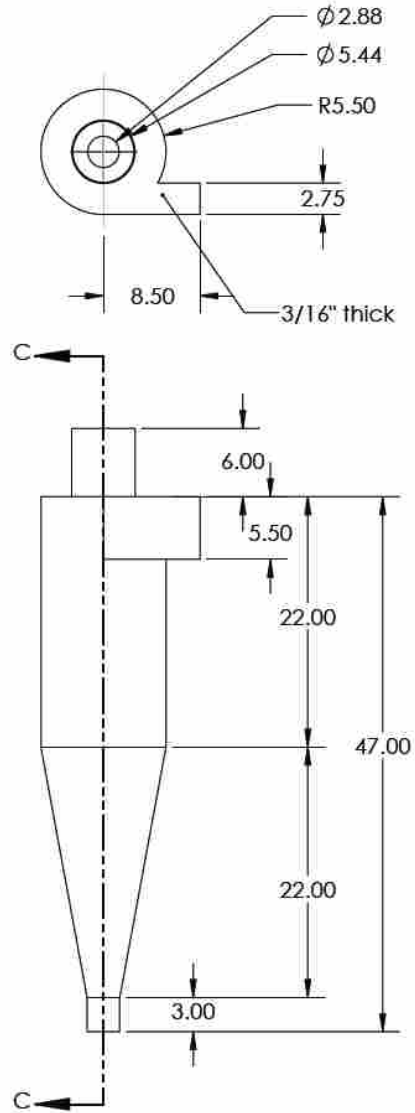


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	cyclone	Cyclone Seperator	1
2	cyclone rectangle flange	Rectangular Flange	2
3	rectangle to flange	Rectangle to circle	1
4	5 in slip on ff flange	5 in. slip on flange, class 125LW	1
5	4 in slip on ff flange	4 in. slip on flange, class 125LW	1
6	2.5 in slip on ff flange	2.5 in slip on flange, class 150	1

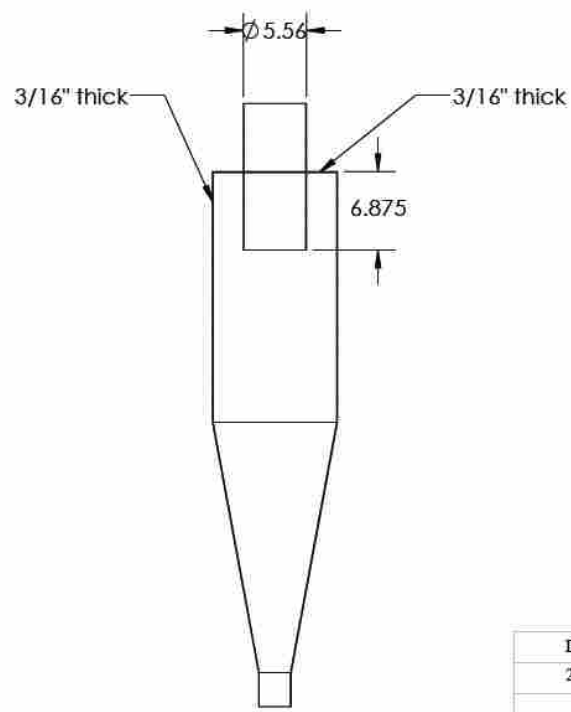


DATE	MADE BY		
2/19/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
Cyclone Assembly			
SIZE A	DWG. NO: 1	SCALE 1:12	REV. A
CAD FILE: Cyclone Assembly			SHEET 1 of 4

Figure B-12: Drawing of cyclone separator assembly.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	cyclone	Stainless Steel 316, 10 gauge unless otherwise specified	1

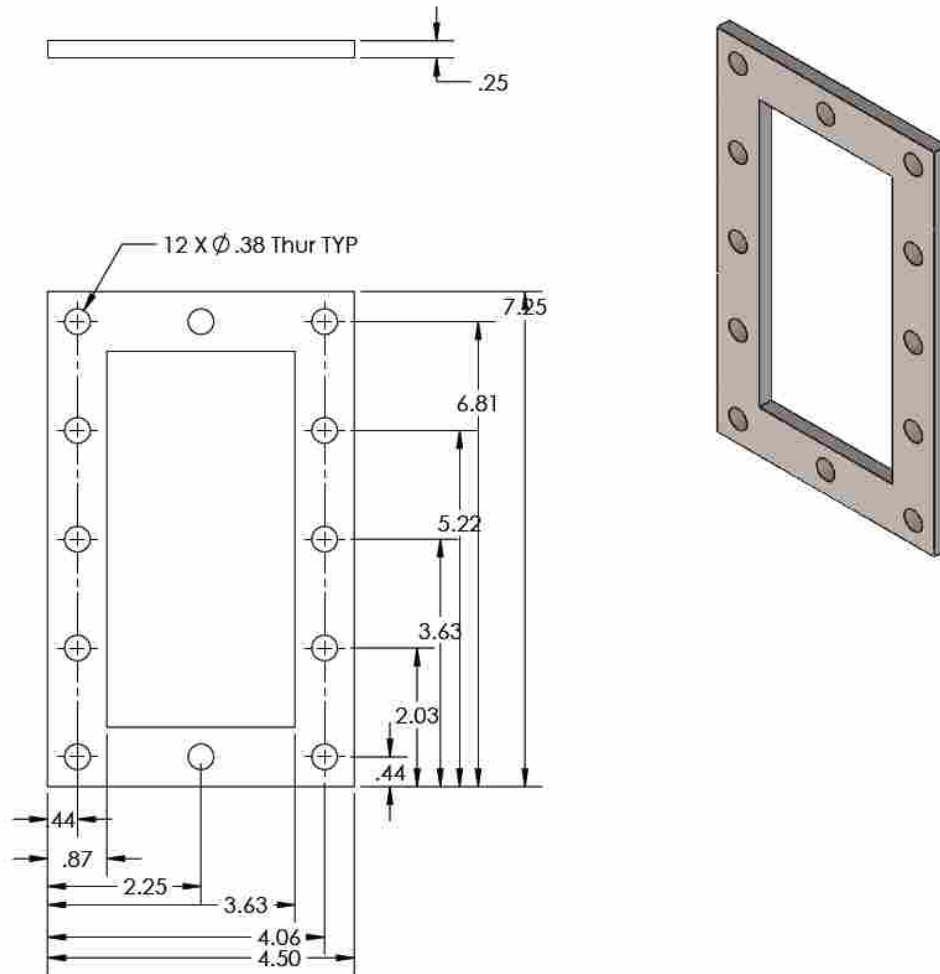


SECTION C-C

DATE		MADE BY	
2/19/2019		Aaron Skousen	
Dry Feed Oxy-Coal Combustion Reactor			
Cyclone			
SIZE A	DWG. NO. 1	SCALE 1:12	REV. A
CAD FILE: Cyclone			SHEET 2 of 4

Figure B-13: Drawing of cyclone separator.

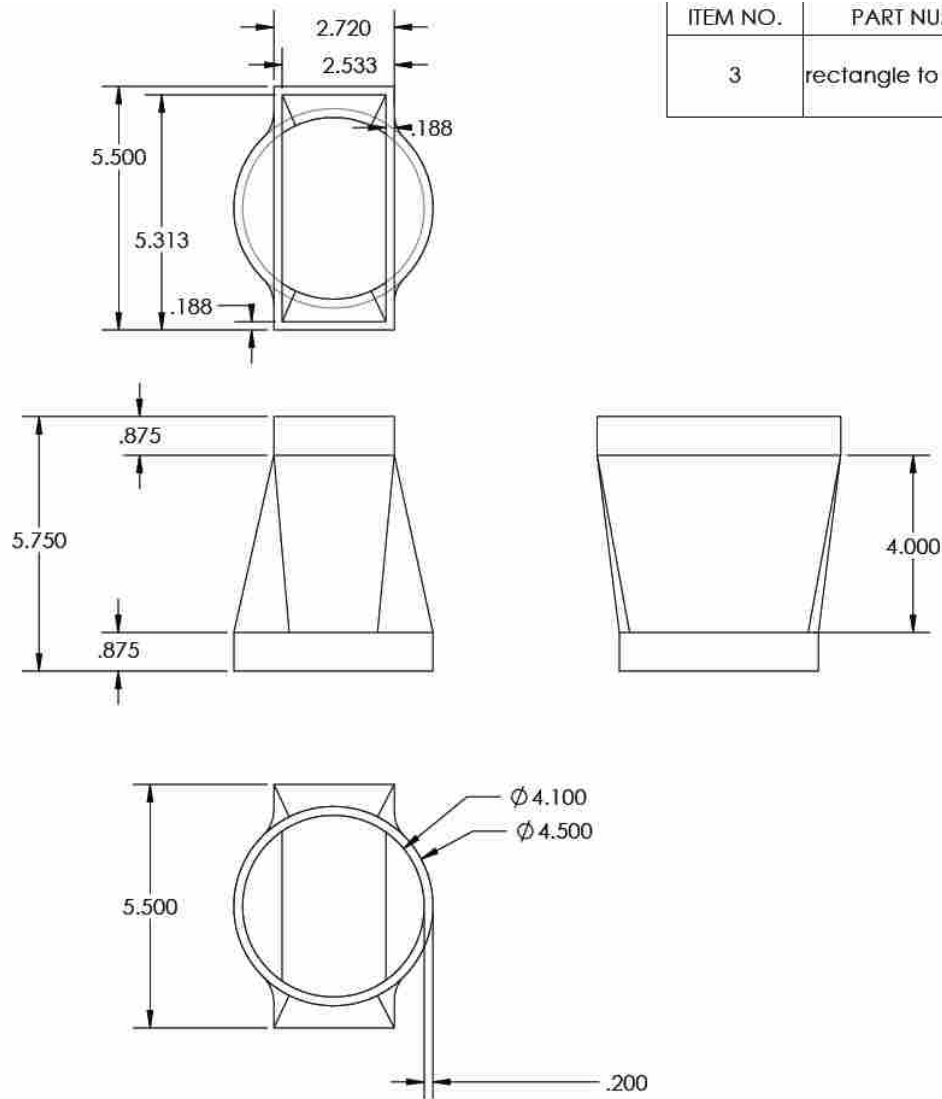
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
2	cyclone rectangle flange	Rectangular Flange	1



DATE	MADE BY		
2/19/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
cyclone rectangle flange			
SIZE A	DWG. NO. 2	SCALE 1:2	REV. A
CAD FILE: cyclone rectangle flange			SHEET 3 of 4

Figure B-14: Drawing of rectangular flange of the cyclone separator.





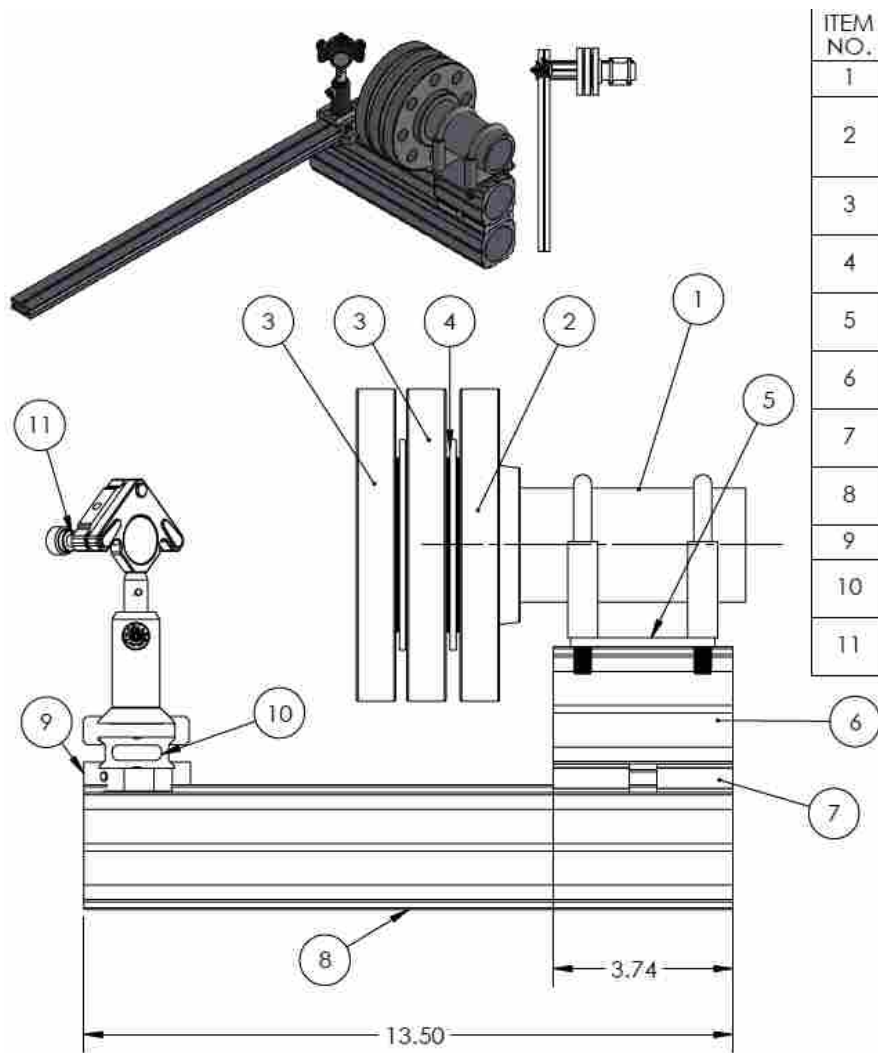
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
3	rectangle to flange	The 5.5"x2.75" rectangle connects to a 4" flange by a lofted base and is 3/16" thick	1

DATE		MADE BY	
2/19/2019		Aaron Skousen	
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
rectangle to flange			
SIZE A	DWG. NO. 3	SCALE 1:3	REV. A
CAD FILE: rectangle to flange			SHEET 4 of 4

Figure B-15: Drawing of the component that connects from a pipe to a rectangle.

#### **B.4 Laser Extinction Method**

The support for the laser extinction method was designed to measure the soot volume fraction at all of the 5 ports in the reactor.

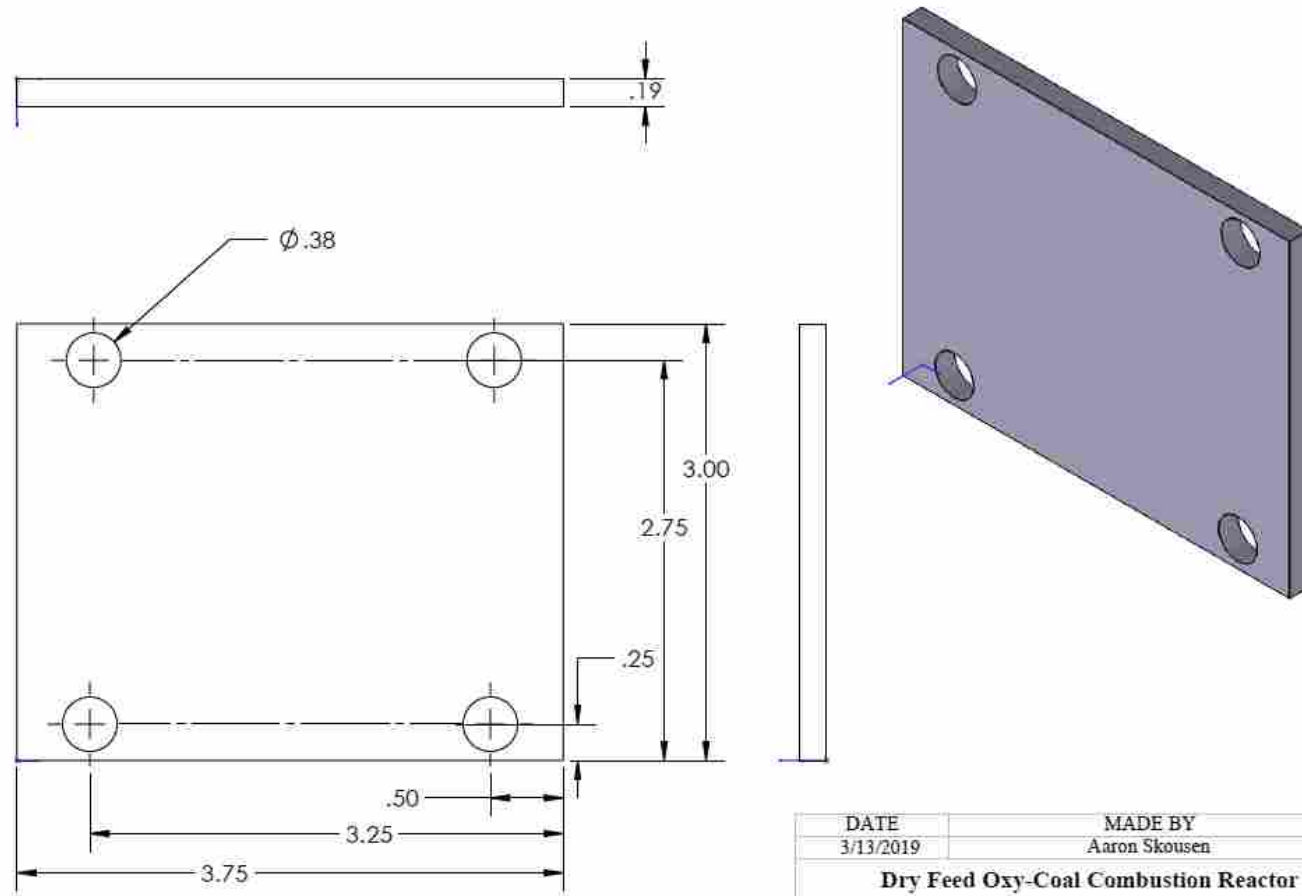


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	reactor pipe	2" pipe, sch 80	1
2	6806K282	2" slip on flange, class 300, carbon steel	1
3	6806K322	2" blind flange, class 300, carbon steel	2
4	44955K482	2" flexitallic gasket, class 300	2
5	plate assembly	aluminum mounting plate	1
6	XT66L100	66 mm square optical aluminum rail	1
7	XT66C2-Solidworks	double dovetail clamp	2
8	XT66L343	66 mm square optical aluminum rail	1
9	XT66CC-Solidworks	66 mm cross clamp	1
10	XT66DPRL1625	66 mm double optical aluminum rail	1
11	mirror assembly	post with post mount and mirror	1

DATE	MADE BY		
3/13/2019	Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>			
Laser rail assembly			
SIZE A	DWG. NO. 1	SCALE 1:3	REV. A
CAD FILE: Laser rail assembly			SHEET 1 of 2

Figure B-16: Drawing of laser extinction mount assembly.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
5	Plate	3/16in. aluminum plate	1



DATE		MADE BY		
3/13/2019		Aaron Skousen		
<b>Dry Feed Oxy-Coal Combustion Reactor</b>				
Plate				
SIZE A	DWG. NO. 1	SCALE	1:1	REV. A
CAD FILE: Plate				SHEET 2 of 2

Figure B-17: Drawing of aluminum plate for laser rail assembly.

## **APPENDIX C. BILL OF MATERIALS**

The bill of materials for the components of the exhaust system.

Name	Cost \$	QTY	Total	Part number	Company	Description
<b>HX Structure</b>						
HX Shell	882.5	1	882.54	Quote	MRC Global	6 in pipe, schedule 80, ss 316
Blind flange	148	3	444.12	Quote	MRC Global	6 in blind flange, 300 # ss316
Slip on Flange	154.7	2	309.46	Quote	MRC Global	6 in slip on flange, 300 # ss316
Slip on Flange	45.23	1	45.23	Quote	MRC Global	2 in slip on flange, 300 # ss316
Slip on Flange	240	1	240	Quote	MRC Global	4 in slip on flange, 300 # ss309
Gasket	2.57	1	2.57	Quote	Pipe valve and fitting co	2 in Flexible graphite metal gasket 316ss
Gasket	3.58	1	3.58	Quote	Pipe valve and fitting co	4 in Flexible graphite metal gasket 316ss
Gasket	4.45	3	13.35	Quote	Pipe valve and fitting co	6 in Flexible graphite metal gasket 316ss
tubes (20ft sections)	35.6	27	961.2	Quote	twmetals	.375 OD and .245" ID ss316 tubing
4 in pipe	56	1	56	Quote	Pipe valve and fitting co	4 in pipe schedule 80 pipe 309 ss
2 in pipe	35	1	35	Quote	Pipe valve and fitting co	2 in pipe schedule 80 pipe 316 ss
hoist material	150	1	150	Quote	Penn Stainless	316/316L .25" x 12" x 24" plate
<b>Baffle Components</b>						
Baffles	258.2	1	258.21	Quote	Penn Stainless Products	ss 309 2ftx2ft 10 gauge, plate to cut baffles
all thread 1/4-20	12.04	2	24.08	94400A150	McMaster	6ft length all thread
all thread 10-32	12.3	2	24.6	93250A012	McMaster	6ft length all thread
nuts 1/4-10	3.63	8	29.04	94819A043	McMaster	hex nuts

nuts 10-32	8.34	3	25.02	90257A411	McMaster	hex nuts
Baffle costs	210	1	210	water jet	Machine Shop	water jet cost

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**Cap for HX**

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Cap	30.67	1	30.67	Quote	Pipe valve and fitting co	6 in schedule 40 cap 2" to 1" pipe reducer, 150 #, ss304
pipe reducer	34.68	2	69.36	4464K548	McMaster	
cap plate	21.96	1	21.96	8992K31	McMaster	6.05x4 plate 304 1/8" 2" one side threaded pipe, sch 40, ss316
one side threaded pipe	10.05	2	20.1	9110T38	McMaster	Measure flow in pipes, 2.5 to 52.8 GPM
1" flow meter	1303	1	1303	MFS-31	Dwyer	cord for flow meter, 16.4" length
flow meter cord	77.5	1	77.5	MFS-C5	Dwyer	
2" pipe 1' length	7.38	2	14.76	SM16-CA11-0360-11B- 38B	Grainger	1" braided flexible pipe

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**Thermocouple**

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pipe clamp	7.8	2	15.6	61585188	MSC direct	
thermocouple	38.5	2	77	BLMI-XL-K-18U-6-CC	omega	flue gas thermal
thermocouple	66.5	3	199.5	XCIB-K-4-5-10	omega	surface thermocouple
thermocouple	41.5	2	83	TC-K-1/8NPT-G-72	omega	water pipe thermocouple
thermocouple	58.5	1	58.5	TJ36-CAXL-18U-12-CC-	Omega	Reactor nozzle
thermocouple	58.5	1	58.5	XCIB	Omega	thermocouple
bung	3	2	6	NPT186	bung king	use for pipe thermocouple
swage fitting	11.22	3	33.66	SS-200-1-2WBT	Swagelok	used for gas temperature measurements

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**Cyclone Separator**

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cyclone	2136	1	2136	Quote	Richard Sheet Metal	cyclone separator
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55 gallon drum	114.2	1	114.22	4115T89	McMaster	55 gallon steel drum
pneumatic cart lift	170	1	169.99	61405	Harbor Freight	500 lb lift
<b>Condensation build up</b>						
slip on flange	74.87	4	299.48	Quote	Pipe valve and fitting co	4" 150# RF SLIP ON FLANGE 316 SS
concentric reducer	32.07	2	64.14	Quote	Pipe valve and fitting co	4 X 1-1/2" SCH 40 BW CONC RED. 316 SS
swage nipple reducer	95.67	2	191.34	Quote	Pipe valve and fitting co	1" X 1-1/2" SCH 40 316 SS SWAGE NIPPLE CONCENTRIC MNPT X PLAIN END
6" cap	79.72	1	79.72	Quote	Pipe valve and fitting co	6" SCH 80 BW CAP 316 SS
seamless pipe	142.5	1	142.5	45725K891	McMaster	4" pipe schedule 40, ss 316
one sided threaded pipe	4.03	1	4.03	9110T25	McMaster	1" pipe threaded on one side
ball valve	526	2	1052	E26NRXV4A	Assured Automation	2" electric ball valve
<b>HX to cyclone</b>						
2" 90 bend sch 40 Straight Reducing Adapters	13.95	2	27.9	45555K516	McMaster	2" 90 bend sch 40 316/316L
1/2" pipe	9.42	1	9.42	9110T73	McMaster	1/2 to 1/4 reducer Threaded on One End,316/316L SS #150
4" to 2" reducer	32.94	1	32.94	45555K122	McMaster	schedule 40
2" manual valve	500	1	500	150200-11002SSKR-NN	Intermountain valve and control	flanged high temp valve #300
4" tee sch 40 316 ss pipes and flanges	75.56	1	75.56	45555K633	McMaster	4" tee sch 40 316 ss
solenoid valve	1521	1	1520.7	Quote 8810876	MRC Global	see POC group folder
electric actuator	80	1	80	E3E	Assured automation	3-way/2 position valve
	695	1	695	S40750UV	Assured automation	electric actuator



actuator mount	35	1	35	FLBK-2-SS	Assured automation	spacers
actuator mount	35	1	35	FLCP075C	Assured automation	mount
2" ball valve	1295	1	1295	H300FGSF08SO	Assured automation	flanged high temp valve #300
1/2" control valve	1532	1	1532	1002GCN126SV04DEP36	Process Specialties Inc	control valve actuator
actuator, control valve	1327	1	1327	SRD991	Process Specialties Inc	control valve actuator

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**Spray Quench system**

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Motor	194.4	1	194.4	GH0014C	Marshall Wolf Automation	1 hp motor
AC drive 460 V	192.4	1	192.4	L510-401-H3-U	Marshall Wolf Automation	1 hp VFD
pump	365	1	365	4DX03ELR	Cat pumps	.3 gpm @ 2000 psi
1/4 solenoid valve	98.38	1	98.38	4639K75	McMaster	110V solenoid valve
Pressure Transmitter	109	1	109	TPT-C05	Dwyer	pressure transmitter
Flow meter	515	1	515	TFM-LP06	Dwyer	flow meter
1/4" tee	32.6	2	65.2	SS-400-3-4TTF	Swagelok	1/4" Swagelok tee
3/8 to 1/4 reducer for pump outlet	14.3	1	14.3	SS-400-7-6	Swagelok	pipe reducer
3/8 to 1/4 reducer for pump inlet	9.2	1	9.2	SS-400-1-6	Swagelok	pipe reducer
nozzle elbow 1/4" to 1/4"	13.6	1	13.6	SS-400-2-4	Swagelok	elbow
1/4 straight	7.1	2	14.2	SS-400-1-4	Swagelok	tube to tube
three phase wire	10.5	1	10.5	7422K23	McMaster	high voltage wire
spray nozzle separate	246	1	245.96	13785-SS1.5	Spraying Systems Co.	spray nozzle
1/4 tubing to 1/8 female	19.08	1	19.08	SS-400-8-2	Swagelok	adapter for spray nozzle
one way valve	60.57	1	60.57	45385K54	McMaster	one way valve
	Sum		19121			

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