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Design, scale-up, six sigma in processing different feedstocks in a fixed bed downdraft biomass gasifier

Sai Chandra Teja Boravelli

DESIGN, SCALE-UP, SIX SIGMA IN PROCESSING DIFFERENT FEEDSTOCKS IN A FIXED BED DOWNDRAFT BIOMASS GASIFIER

by

SAI CHANDRA TEJA BORAVELLI

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Approved by:

Dr. Joseph Smith, Advisor
Dr. Douglas Ludlow
Dr. Ali Rownaghi

ABSTRACT

This thesis mainly focuses on design and process development of a downdraft biomass gasification processes. The objective is to develop a gasifier and process of gasification for a continuous steady state process. A lab scale downdraft gasifier was designed to develop the process and obtain optimum operating procedure.

Sustainable and dependable sources such as biomass are potential sources of renewable energy and have a reasonable motivation to be used in developing a small scale energy production plant for countries such as Canada where wood stocks are more reliable sources than fossil fuels. This thesis addresses the process of thermal conversion of biomass gasification process in a downdraft reactor. Downdraft biomass gasifiers are relatively cheap and easy to operate because of their design. We constructed a simple biomass gasifier to study the steady state process for different sizes of the reactor. The experimental part of this investigation look at how operating conditions such as feed rate, air flow, the length of the bed, the vibration of the reactor, height and density of syngas flame in combustion flare changes for different sizes of the reactor. These experimental results also compare the trends of tar, char and syngas production for wood pellets in a steady state process.

This study also includes biomass gasification process for different wood feedstocks. It compares how shape, size and moisture content of different feedstocks makes a difference in operating conditions for the gasification process. For this, Six Sigma DMAIC techniques were used to analyze and understand how each feedstock makes a significant impact on the process.

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1. INTRODUCTION AND BACKGROUND

1.1. ENERGY DEMAND

The demand for energy sources has been increasing steadily and it has become one of the vital challenges all over the world. Wood, a biomass was considered the primary source of energy through combustion[1]. The increasing in energy demand, population, and progress in lifestyle has led to the introduction and high dependency on non-renewable resources or fossil fuels such as coal, petroleum, and natural gas as shown in Figure 1.1. This tremendous dependency on fossil fuels for energy production is directly related to the carbon dioxide (CO_2) emissions to the atmosphere which has led to increased concern about greenhouse gases and global warming. Approximately, the carbon dioxide emissions have doubled in the past forty years. Furthermore, a limited supply of fossil fuels and rapid consumption of energy has demanded the alternative and sustainable energy sources[2-4].

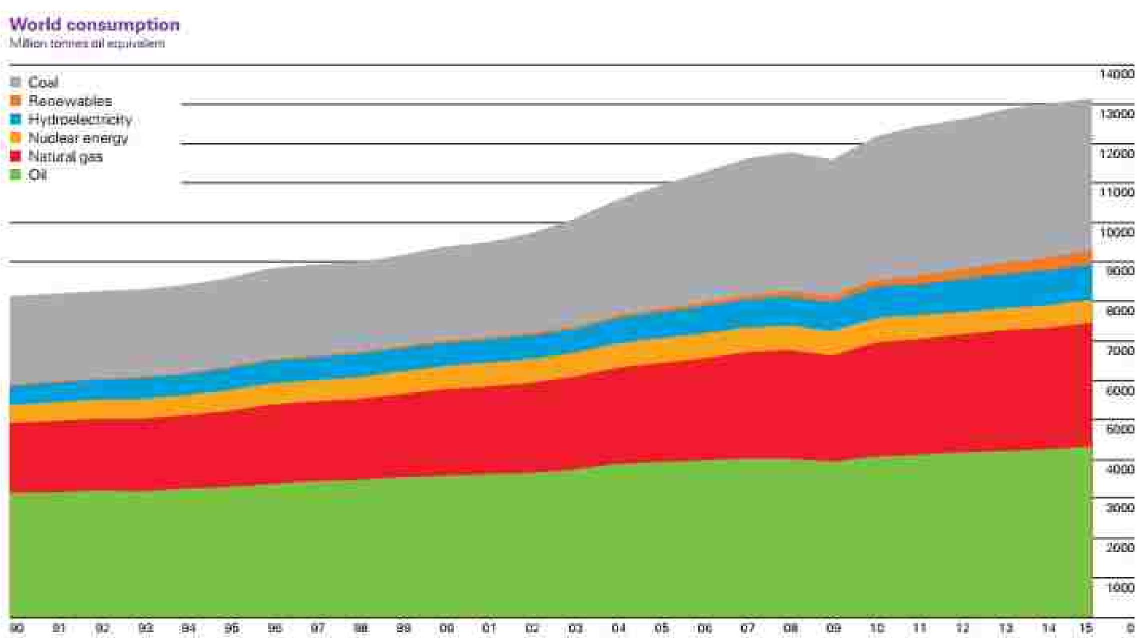


Figure 1.1. World primary energy consumption by resource type[5]

Figure 1.1. shows the world primary consumption of energy through recent history indicating the high dependency on fossil fuels and slowly increasing contribution of renewable resources. A reliable, affordable clean energy supply is of primary importance for the economy and the environment and will prove to be pivotal in the 21st century. Biomass, which is an alternative source of fossil fuels is widely available, CO_2 neutral and environmentally friendly source of energy[6, 7].

1.2. BIOMASS

Biomass is the organic matter derived from the living or dead plant or animal waste. It is composed of molecules of carbon, hydrogen, oxygen, nitrogen, small amounts of sulfur and other heavy metals. There are different classes of biomass available: woody biomass, non-woody biomass such as agricultural crops and residues and biomass from animal manure and organic waste[8]. Wood remains the major source of biomass energy in terms of renewable energy. The two main modes of converting biomass to energy are biochemical conversion and thermochemical conversion. Biochemical conversion of biomass involves anaerobic digestion or fermentation process to produce liquid or gaseous fuels whereas thermochemical conversion or incomplete combustion of biomass to produce syngas is a relatively benign method. One of the main advantages of thermochemical conversion is any type of feedstock can be used in this process and the product gases can be converted to different fuels and chemicals which are a substitute for fossil fuels[9, 10]. In thermochemical conversion, biomass is converted through different methods such as combustion, liquefaction and gasification etc. to various chemicals, of which gasification has attracted much interest as it offers more eminent efficiencies than other methods.

1.3. GASIFICATION

The gasification process is an important method to convert carbonaceous biomass at high temperatures to produce combustible gases by incomplete combustion. Biomass gasification process is CO_2 neutral process as the carbon content from the biomass is absorbed by the photosynthesis process from the atmosphere[11]. This process includes a series of exothermic and endothermic reactions to produce the final gas product known as syngas or synthesis gas[12, 13]. This gas is the mixture of carbon monoxide and hydrogen which on proper cleaning can be used in various applications such as internal combustion engines, electricity, fuel cells etc. The biomass gasification process contains a series of steps: drying, pyrolysis, combustion or oxidation and gasification or reduction whereas the gasifying medium can be air or steam. Though there is a considerable overlap between these zones due to different thermochemical reactions these are treated as different zones[14, 15]. The different zones and reactions taking place in the biomass gasification processes are discussed below and shown in Figure 1.2.

Drying: Drying zone is the zone where there is the removal of moisture and no chemical reaction takes place. This is a mass transfer operation where most of the dehydration process is due to conduction than convection. The weight loss by the biomass in this zone is the percentage of moisture content in the feedstock.

H_20 (l) $\rightarrow$ H_2O (v)

De-volatilization: Pyrolysis or devolatilization reaction is a reaction where the organic material is burnt without air/oxygen to give products such as Char, CO, H_2O, and CO_2 along with primary tar and secondary tar. These reactions take place at temperatures between 200^oC – 500^oC. The products of devolatilization causes around 85% of weight loss and the products like tar and char undergo a partial reduction in combustion and gasification zones. Primary tar cracks at high temperature and produces secondary tar which mainly constitutes of phenol and other products such as carbon monoxide, methane, and hydrogen[16, 17].

Volatile → $0.268CO + 0.295CO_2 + 0.094CH_4 + 0.5H_2 + 0.255H_2O + 0.004NH_3 + 0.2$ primary tar

Primary tar → 0.261secondary tar + $2.6CO$ $0.441CO_2 + 0.983CH_4 + 2.161H_2 + 0.408C_2H_4$

Combustion: In the combustion zone, oxidation reactions take place where the carbon present in volatiles and chars reacts with air/oxygen to produce carbon dioxide; hydrogen and methane react with air/oxygen to produce water vapor and carbon monoxide respectively. These reactions take place at temperatures ranging from 800^{o}C to 1200^{o}C.

$C + O_2 \rightarrow CO_2$

$H_2 + 0.5\ O_2 \rightarrow H_2O$

$CH4 + 1.5\ O2 \rightarrow CO + 2H_2O$

Gasification: Reduction zone is the gasification step, where the products from oxidation steps react with red hot char present above the grate to undergo reduction. These reactions take place in the absence of oxygen in temperatures ranging between 650^{o}C to 900^{o}C[18]. The reactions happening in this zone are as below.

Water gas reaction: $C + H_2O \rightarrow CO + H_2$

Water shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$

Boudouard reaction: $C + CO_2 \rightarrow 2CO$

Methanation reaction: $C + 2H_2 \rightarrow CH_4$

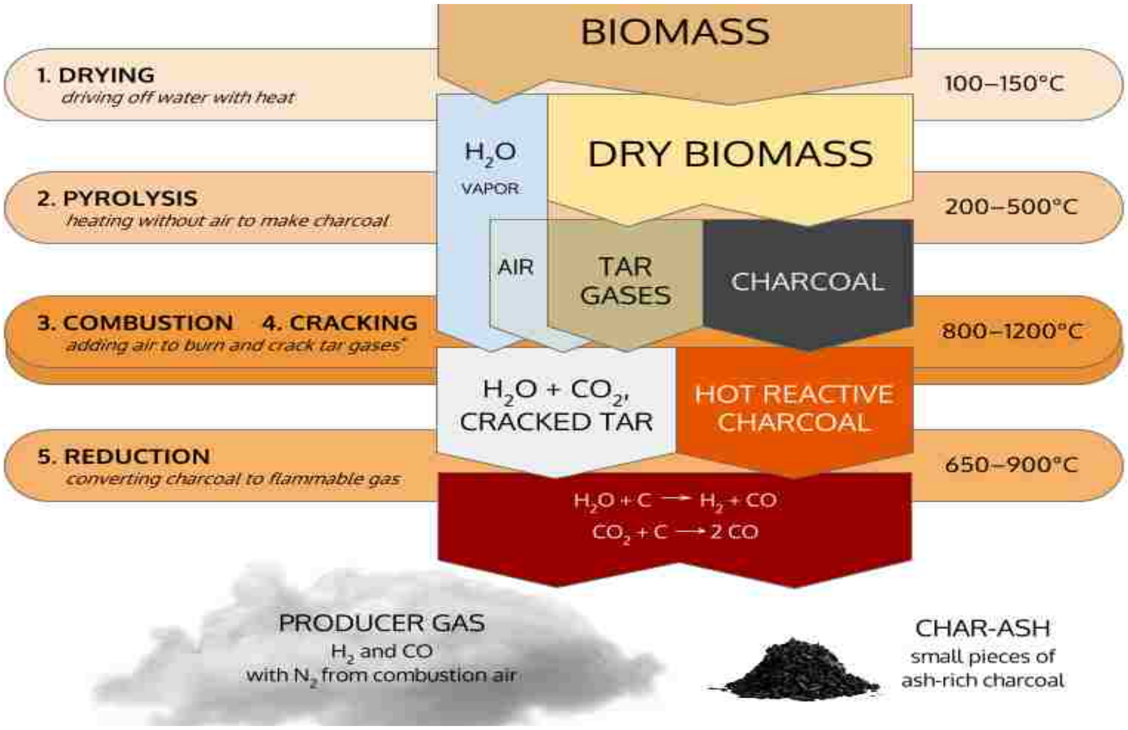


Figure 1.2. Different zones in a biomass gasification process[19]

1.4. TYPES OF GASIFIERS

Gasifiers are classified into different types based on the flow of gasifying agents such as air or steam. The two important types of gasifier are fixed bed and fluidized bed gasifiers[20-22]. Fluidized bed gasifiers are the ones in which feed is introduced from the side to a preheated granular bed in an oxygen or air rich stream. This resulting bed acts as a fluid and the main advantages of these gasifiers are the fluidization bed raises the heat transfer to biomass feed particle which results in an increase in reaction rate and efficiency of the process[23]. The fixed bed gasifiers are further divided into updraft/ counter current and downdraft/co-current gasifiers based on the flow direction of gasifying agent i.e. for updraft gasifying agent enters from the bottom which results in combustion happening above grate and for downdraft gasifying agent enters from the top as discussed below[24].

1.5. DOWNDRAFT GASIFIERS

In this gasifier, biomass feedstock is introduced from the top, moves downwards and rests on the grate present below as shown in Figure 1.3. As the gasifying agent or air also enters from the top to bottom, these gasifiers are called as downdraft gasifier or co-current gasifiers. In this type of gasifier, gasification process takes place at the bottom of the gasifier or just above grate and combustion reactions takes places above the gasification zone. Gaseous products and tars produced exit from the bottom of the gasifier and most tars produced are cracked as it passes through the high-temperature region, unlike updraft gasifiers where there is a low-temperature exit. But care should be taken that the heat is recovered from the high-temperature product gas. The main advantages of downdraft gasifier are it produces the tar free gas but has some difficulties of excessive pressure drop and transportability while processing the low-density feedstocks[25].

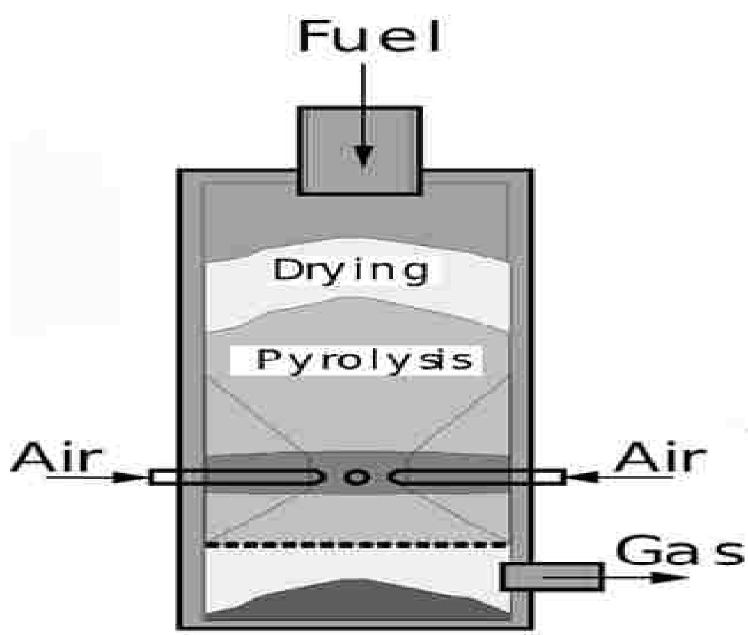


Figure 1.3. Fixed bed downdraft biomass gasifier [21]

1.6. APPLICATIONS OF GASIFICATION

The production of syngas or product gas from biomass has many advantages as it being carbon neutral. According to U.S. Department of energy, the various applications of gasification are shown in Figure 1.4. The main applications are observed in power generation where there is direct or indirect combustion of product gas. In this syngas or product gas is used to evaporate water for its utilization in co-fired coal plants and combined heat and power plants for electricity generation. Apart from power generation, another major application of gasification is Fisher Tropsch process[13, 26, 27]. In this, the syngas produced from biomass gasification process is cleaned from all its impurities and used in a Fisher Trospch reactor to produce clean biofuels. Other utilizations include the production of ammonia and methanol, hydrogen in refineries, a synthetic natural gas which has similar properties of natural gas and other small applications such as preparation of olefins, aromatics, and mixed alcohols. Due to various applications of gasification, as shown in Figure 1.4., research and development in this process have been continuously increasing to cope with the high and clean energy demand.

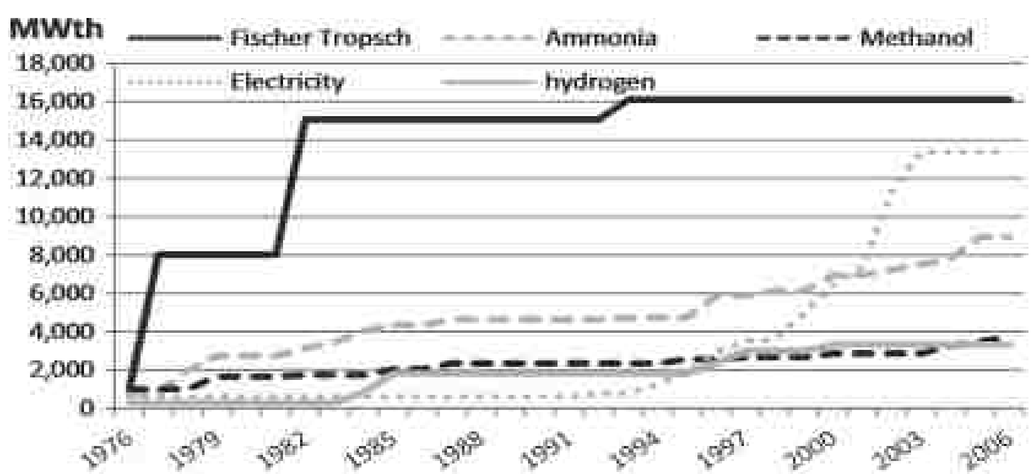


Figure 1.4. Major applications of gasification process[26]

2. DESIGN

The design of a downdraft biomass gasifier is primarily divided into three sections namely reactor, condensation unit and combustion flare. The reactor is the section where biomass enters and undergoes gasification process. Condensation unit is the transport line of syngas to enter combustion flare. In the combustion flare, the syngas produced from the gasifier is burnt with the help of propane tank.

2.1. REACTOR

Our initial design of downdraft gasifier consists of three enclosed cylinders known as reactor core, air plenum, and syngas plenum. The reactor core is the innermost cylinder which is 8” in diameter and 19” inches in length. It is surrounded by air plenum which supplies air to air nozzles present in the reactor core to support combustion process. A grate is connected to reactor core at the bottom, for chars to pass through it for continuous steady state process. The reactor core is surrounded by syngas plenum where the products formed after gasification are pulled by induced draft fan and lead to syngas outlet. Three thermocouples are placed inside this reactor at fixed lengths to collects temperatures of drying, combustion and gasification zones inside the reactor. These thermocouples are placed from the top of the reactor at a height of 2” for gasification, 6” for combustion and 12” for drying zone from the bottom of the grate.

After experimental investigations, the air plenum and nozzles inside the reactor core were removed. The reasons being to avoid excess heat loss in the reactor as the hot reactor core is surrounded by cold air plenum and to avert bridging caused by nozzles which created problems in smooth flow of biomass bed inside the reactor.

2.2. CONDENSATION UNIT

In the initial design, the outlet of syngas was connected to a cyclone separator to separate the solids (ash) from the produced syngas. This idea of cyclone separator was removed as tars produced from the reactor which clogged entire separator. Cyclone separator was replaced with a U-shaped transportation or condensation unit where the other of end this line is connected to the induced draft fan.

The products such as gases and tars produced from the reactor are passed through U-shaped condensation/transportation unit connected to syngas outlet. This condensation unit is connected to the induced draft fan which creates a draft to pull the products formed inside the reactor. An upstream ball valve is set up before fan to control the flow through entire transportation unit which also pulls air from the atmosphere for combustion process inside the reactor core. In the downstream after induced fan outlet, a T-junction is placed to collect a sample of gas produced, which is functioned by a ball valve. Additionally, in the initial stages of investigations, transportation unit consisted of two valve openings for bio-oil/tar collection and a liquid trap as a safety reason to remove any excess pressure or to avoid puffing in the system. Later, the liquid trap was removed after a deep understanding of the operational procedure of the system. The important purpose of condensation unit or transportation unit is to cool the hot products coming out of syngas outlet through the process of natural and forced convection before entering fan to avoid burning of the fan. A small table fan is used as a forced convection to condense tars in the system. To make sure all the regions are in the desired temperature range, it is equipped with three thermocouples to collect temperatures of syngas outlet, fan inlet and fan outlet. Additionally, two oxygen sensors are placed, one after the syngas outlet and the other before the burner to assess the concentration of oxygen to be less than 1% of upper flammable limit to avoid any explosion, also to ensure there is no leak in the system.

2.3. COMBUSTION FLARE

For the initial experiments, the wood stove was used as a combustion flare to burn the syngas. Later, a cylinder of 24” diameter with small holes at the bottom to supply oxygen to burn gas is used as an enclosed combustion flare. The flare consists of ring burner connected to propane cylinder which helps in burning the syngas produced from the gasifier. This combustion flare is placed on sand and fiberglass layers which act as an insulation to avoid heating of ground. Smoke from combustion flare is sucked by the suction pump present above the flare. Figure 2.1. shows the setup of downdraft biomass gasification unit.

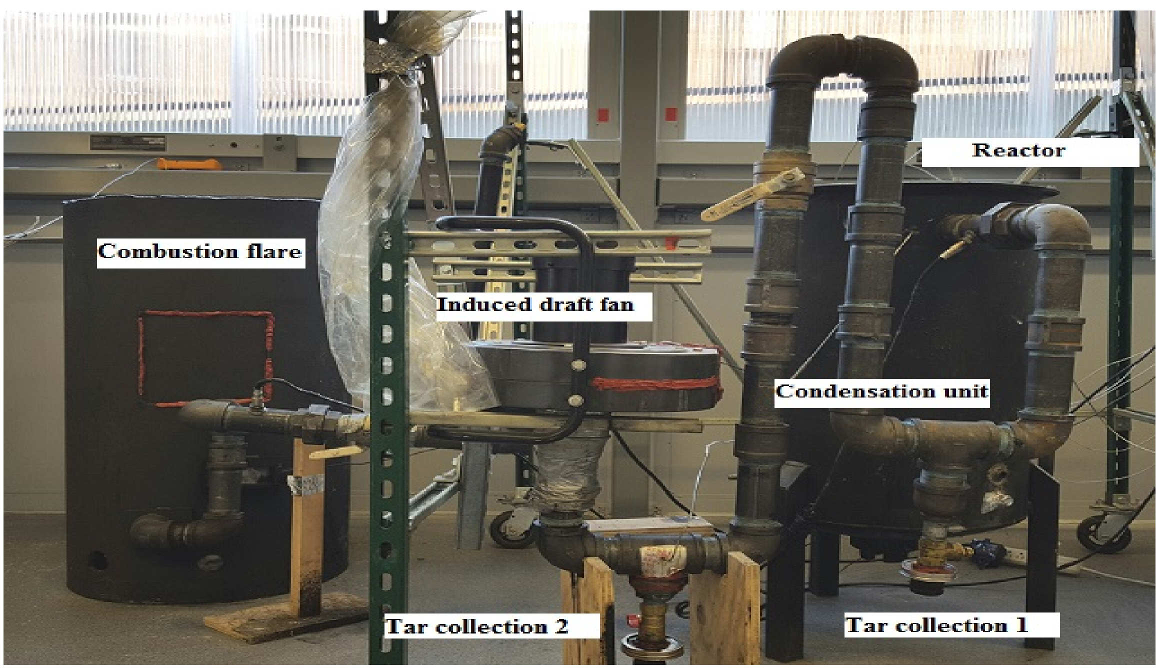


Figure 2.1. Setup of downdraft biomass gasification unit

3. METHODOLOGY

Before going to the methodology, processing of woody feedstocks depends on the properties of feedstocks such as shape and its properties. Figure 3.1. below shows the different feedstocks namely pellets, flakes, and chips used for the experimental investigation. As shown in the Figure 3.1., left most pellets are the processed biomass feed which is generally made from compacting sawdust and are evenly shaped and has less moisture content. Flakes are also processed feed obtained by removing bark of wood first and has slightly high moisture content than pellets. Wood chips as shown in Figure 3.1. are unprocessed biomass feedstocks which are unevenly shaped and has high moisture content nearly 35%.

Figure 3.1. Left to right woody feedstocks: pellets, flakes, and chips

At first, the chemical and physical properties of these wood stocks are determined to understand the feed and its contents distinctly. The proximate and ultimate analysis for the feedstocks is carried out using a thermogravimetric analyzer and CHN analyzer respectively. The thermogravimetric analysis gives the amount of moisture, volatile, char and ash present in the feed whereas CHN analyzer gives the ultimate values of carbon, oxygen, hydrogen and nitrogen values in it. CHN analyzer calculates the values of carbon, hydrogen, and nitrogen in sample and oxygen values are obtained by subtracting the sum of percentages of CHN from 100. In order to undergo these tests, the sample material should be void of moisture content for which the samples are subjected to vacuum drying to the temperature of 300^{o}F. Along with the above analysis, heating values of these feedstocks are found of using a bomb calorimeter. Samples are selected randomly for the above feedstocks and repeated tests are conducted to get the best average values for the analysis. The effects of different shape and properties such as moisture content of biomass make a significant impact on the operating conditions of gasifier which are discussed later in detail in Section 5. The ultimate, proximate and heating values of feedstocks namely pellets, flakes, and wood chips are listed below in Tables 3.1., 3.2., and 3.3. respectively.

Table 3.1. Proximate analysis of chips, flakes, and pellets

	Chips	**Flakes**	**Pellets**
Moisture %	35.19	11.01	7.56
Volatile dry %	82.28	86.15	87.23
Fixed Carbon dry %	17.26	13.32	12.39
Ash dry %	0.46	0.53	0.38

Table 3.2. Ultimate analysis of feedstocks

	Chips	**Flakes**	**Pellets**
Carbon %	48.81	48.24	49.03
Hydrogen %	5.96	6.15	5.58
Oxygen %	44.98	45.55	45.33
Nitrogen %	0.26	0.06	0.06

Table 3.3. Calorific value of feedstocks

Heating value	**Chips**	**Flakes**	**Pellets**
Cal/gm	4509.90	4562.12	4621.76
Btu/lb	8117.82	8211.82	8319.16

This experimental study is divided into two Sections where we compare steady state gasification process of wood pellets in different sizes of the reactor (4”, 8” and 12” diameter) and the latter Section 5 deals with the differences in operating conditions for different types of feedstocks in 8” reactor where the basic operating conditions remains the same as in Section 3.

3.1. STARTUP PROCEDURE

Before the startup procedure, care is taken to make sure the entire unit is properly connected. Initially, the data acquisition system (LabVIEW) for thermocouples, oxygen sensors, and cameras are turned on to ensure the process is recording. Tar collecting jars are connected to the valves and made sure these valves are open. For a startup, the propane burner inside combustion flare is ignited to provide a combusting source to burn syngas that is produced inside the system. The suction fan for combustion flare is then turned on to suck the smoke inside flare. Induced draft fan is turned on and an upstream ball valve is opened and set to valve setting 4 for the flow of products formed inside the reactor core to combustion flare. The experiment is now started by feeding approximately 8” in length of biomass feedstock from the bottom of grate or length of 1” above the combustion thermocouple for startup process. A lighter liquid is then used to ignite the feedstock and monitor the temperature and oxygen values on LabVIEW. Once the temperatures in combustion and gasification zone show a temperature of around 1200^{o}F and 800^{o}F respectively, the startup procedure is continued. During this process, we also observe the oxygen values in the sensors show the range between 0.6 – 0.8 % which is below UFL limit.

3.2. STEADY STATE PROCESS

Once the temperatures of combustion and gasification zone reach the desired limit we add a new batch of feedstock for the gasification process. When a new feed is added on the top, temperatures inside the reactor fall immediately due to room temperature and moisture content of feed but increases as the process continues. It is desirable to feed small batches of feed to the reactor instead of adding large batches approximately 2lb for every five minutes, as the small bed is easy to operate and avoid piling up of the reactor. The temperatures inside the reactor and oxygen values are controlled by the upstream valve and length of bed inside the reactor. As bed goes down more air is flown through the system with same valve setting, so the temperatures inside the reactor increase because of excess O_2 supply and vice versa. This can be controlled by adding new feed instead of changing valve settings as we are interested in maintaining a steady state process. For the steady state, the gasification zone is present at the length of 2” above grate where temperatures are in the range of 1400°F – 1550°F and combustion temperatures are maintained below 1600°F – 1800°F which is present above gasification zone for approximately 4”-6” in length. The char pass through the grate from the bottom which helps in moving the bed down for a continuous steady state process. This procedure of adding a new feed to maintain the bed is repeated for the steady state process. For initial study, a spin vibrator was connected to the flange which assists in moving the bed down and allows chars to pass through grate for steady state process but later it was observed that the longitudinal vibrations work best to move the bed down. This kind of vibration to the reactor flange transfers energy to the grate which helps in moving the bed down and avoid piling of the reactor. The oxygen and temperatures are constantly monitored throughout the process and vary the operating conditions as per these values. The detailed explanation will be given in the Section 4 for steady state process for different sizes of reactor and types of feed.

3.3. SHUTDOWN PROCESS

For the shutdown process, nitrogen is purged from the top of the reactor to kill the reactions. For this, a metal door with rope gasket attached to it is built with combustion, gasification shutdown thermocouples and nitrogen purge connection fixed to it. Whenever we want to go to shutdown procedure, we stop adding feed inside the reactor and let the reactions happen until we see the burning charcoal inside the reactor. At first, the thermocouples placed inside the reactor for the operational procedure are removed from the top and the new shutdown door installed with thermocouples and nitrogen purge pipe is kept on the top of the reactor. This door is placed in order to seal the system completely so that no air enters the system to support combustion. The temperature of thermocouples used during the operational procedure decreases whereas the shutdown thermocouple temperatures start rising. As the nitrogen is purged, the nitrogen cloud inside the reactor passes through the system not allowing oxygen to pass through the system to kill the reactions. After killing of reactions, the induced draft fan is turned off and with a small time lag, the upstream ball is opened completely. The fan is closed to avoid any pull of air which might again start the reactions and the valve is opened completely to allow nitrogen and smoke to pass through the condensation unit. Once we see smoke coming off the reactor, the flow of nitrogen is reduced gradually, it is due to backflow of nitrogen as the reactor is accumulated with smoke. After some time, the upstream valve is closed to isolate the whole gasifier from combustion flare and transportation unit which ensure no air flow through the system; nitrogen purged inside the reactor core is trapped to decrease temperatures of shutdown thermocouples. Propane is turned off after the syngas production stops. The entire procedure of purging nitrogen takes around two minutes until the reactions get killed. The time taken for the shutdown thermocouples to reach the room temperature depends on the amount of biomass bed inside the reactor, type of biomass and size of the reactor. At the end the chars, bio-oil are measured for mass balance of biomass feedstock. Based on the above discussed operating procedure, in the next Section, we discuss how the procedure changes for different sizes of reactor for wood pellets.

4. RESULTS AND DISCUSSION FOR REACTOR SCALE-UP

The experiments were conducted for wood pellets in a 4” and 8” diameter downdraft biomass gasifier. The basic operating procedure for these reactors is as discussed in Section 3. In this Section, we discuss how the operating conditions depend on the size of reactor, length of bed inside the reactor and air flow through the bed. Figure 4.1. below shows the different diameters of reactor used for this study. These reactors are made of carbon steel with 12”, 4” and 8” inches in diameter showing from left to right. These reactors in Figure 4.1. are used as the reactor core while the experiment on the particular size of the reactor was conducted. At the bottom of the reactor, a sieve is attached by a chain which supports the bed from the bottom. Through this sieve, the chars left to pass through and fall in the syngas chamber for a steady state process.

Figure 4.1. Different sizes of reactor for steady state process

4.1. STEADY STATE PROCESS FOR A 4” REACTOR

As discussed in Section 3, for the startup process all the instructions of preprocessing are checked before adding the feed to the reactor. Pellets, which are processed feed with similar shape and less moisture content are used as the feedstocks for this study. The thermocouples connected to LabVIEW collects the data every one second. After making sure that the data acquisition system, propane burner, suction duct and induced draft fan are turned on in this order, the upstream ball valve is half opened to create a flow for products from the reactor to combustion flare.

After the startup process has been commenced as discussed in Section 3, we let the temperatures inside reactor increase until they reach the desired limit of greater than 1200^{o}F for combustion zone. For pellets, the upstream valve has to be slightly opened more to flow of air to the bed, as pellets being denser they are tightly packed inside the reactor. Too much opening of valve is not desired for 4” reactor as excess air inside the system results in combustion than gasification of process. The amount of fresh feed present on the combustion and gasification bed also plays a very important role as presence of too much feed on the top has more restriction for air flow. This requires increase in flow of air for proper combustion in other case this might result in loosing of combustion bed or moving the bed toward the top of reactor leading to piling of feed inside reactor. This flow of air is controlled by the upstream valve present in the condensation unit. During this process we see the levels of oxygen in oxygen sensors decrease to 0.6 -0.8% of oxygen which is below UFL.

For the steady state process, when the small batch of new feed is added to the reactor, the temperatures immediately fall to some extent due to moisture and ambient temperature of feed (80^{o}F) and then increase for the steady state process. After the temperature increase and an established combustion bed is formed in the reactor, the thermocouple inside the reactor shows the temperature of above 1600^{o}F and 1400^{o}F respectively which will be discussed below and shown in Figure 4.2. For the 4 inches reactor since there is less feed undergoing the gasification process the amount of air flow required is less. If there is too much air the combustion and gasification bed moved down to the grate with very less gap between each of these zones. One disadvantage for too much air flow is there is a risk of combustion happening instead of gasifying the product. With the increase and decrease in air flow, the combustion and gasification beds can be controlled or move down and up respectively. With decrease in air flow, the amount of oxygen reaching down through the depth of the bed is less due to restriction caused by bed, so the combustion bed moves up and vice versa when there is high flow.

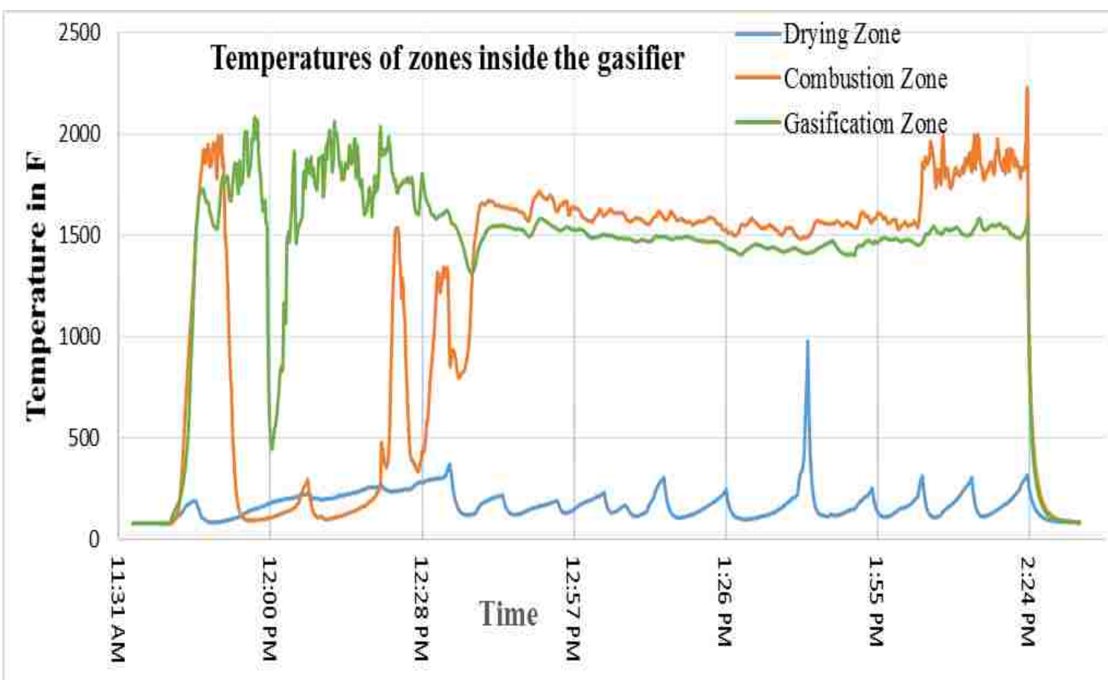


Figure 4.2. Temperature profiles of zones inside the reactor for wood pellets

The temperature profiles of drying, combustion, and gasification zones inside the reactor are shown in Figure 4.2. Temperatures for drying, combustion, and gasification zones are on y-axis plotted against time on the x-axis. In the graph below the experiment was started at around 11:35 am where we can see the increase in temperature profiles of all three zones. Once the established combustion bed is formed a new feed is added to the reactor where we see an immediate drop in temperatures of combustion and gasification thermocouples. During this time, the new feed was added until 1” above the fixed combustion thermocouple. The established combustion bed is formed and the temperature reaches to around 2000^{o}F. At this point the feed inside the reactor consumes and the combustion bed is slightly below the fixed combustion thermocouple. This high temperature of 2000^{o}F is due to radiation and the feed is added at this time where the fixed thermocouple shows the temperature of new added feed in the reactor. In the first hour of experiment, there was variation in temperature profiles of combustion and gasification zones and this was made intentional to see the change in combustion and gasification bed with air flow and mass flow to the reactor. Here, the air flow and mass flow was varied so that there is change in restriction caused by biomass feed on top of this bed, which changes in supply of oxygen to combustion bed to avail the movement of bed. Combustion bed moves down in altitude inside the reactor when there is too much air flow and raises up as there is decrease in air flow to the system. At time 12:30 pm, the gasification and combustion bed raises as a steady state process was maintained for the rest of the run. This is indicated by the combustion and gasification thermocouples which show the steady state temperatures for the rest of the run. During this time, a small feed rate of biomass is fed to the reactor at regular intervals to maintain the steady state process. The small increase and decrease in temperatures in drying zone indicates the addition of new feed to the reactor. At time 2:00pm we see there in increase in temperatures in combustion zone that is because of the slight increase in air flow to the reactor.

During the steady state process, another important factor that's makes a huge impact is the vibration of the reactor to pass chars through the grate and avoid filing of the reactor. For this, the reactor flange is subjected to longitudinal vibration from the top which carries vibration parallel to the direction of energy applied, i.e. energy is transferred to the grate from top of the reactor which vibrates the grate up and down thereby passing the chars present above grate to fall through it. It was also observed that other vibration such as spin vibration doesn't impact to the whole bed but only vibrates some region of the reactor. So, this longitudinal vibration is best and required for every two minutes to pass chars through the grate and maintain a steady state process. This vibration is also needed for the proper supply of oxygen/air to the combustion and gasification beds inside the reactor when a new feed is added to the reactor. In Figure 4.2., a small batch of new feed was added on top and was subjected to limited vibration. This addition of feed increased restriction to pass air through the depth of reactor and the combustion bed immediately raises up. Once there was proper vibration given to the system the bed goes down and the temperatures of drying zones immediately goes back to the normal drying zone temperature limit.

In the steady state process, we observe the syngas flame in the combustion flare depends on the air flow into the reactor. When the air flow is less i.e. until the time when combustion temperatures were around 1600^{o}F we see a yellow flame inside the flare. As the upstream valve is increased for high air flow, a think high dense blue flame was observed inside the flare. The size of the syngas flame inside the combustion chamber is less than 1 feet for 4 inches reactor and the quality depends on the air flow to the system. Figure 4.3. below shows how the syngas flame changes depending upon the flow of air to the system.

Figure 4.3. Syngas flame in combustion flare a) left less air flow b) high air flow right

Other factors which are affected or controlled with the process inside the reactor are syngas outlet, fan in and fan outlet temperatures. As air flow increases, the combustion bed goes down increasing the temperature of feed just above the grate and releasing high-temperature products from the bottom thereby increasing the temperature of syngas outlet. This high temperature of syngas outlet should be cooled in the condensation and the liquid products such as bio-oil has to be removed before entering the fan. High gas temperature and liquid products entering the fan may cause burning/melting of blades and clogging of a fan with tars respectively. In Figure 4.4. below which shows the temperature profiles inside condensation unit, till time 12:15 pm syngas outlet temperatures increase considerably as the bed inside combustion and gasification bed inside the reactor was near the grate due to high air flow. So the syngas outlet temperatures, fan in and fan out can be controlled by air flow inside the reactor. The temperature of syngas outlet and fan inlet temperatures starts to rise around 2:00 pm which is due to increase in temperatures with a slight increase in air flow. So the condensation unit has to be effective enough to cool syngas and collect tars and bio-oil are at the tar collecting valves placed inside the condensation unit. Tar or bio-oil is only produced during the startup procedure as there are low gasification temperatures initially before the steady state process. Once the steady state high temperatures are reached the production of tar or bio-oil stops in the tar collecting unit.

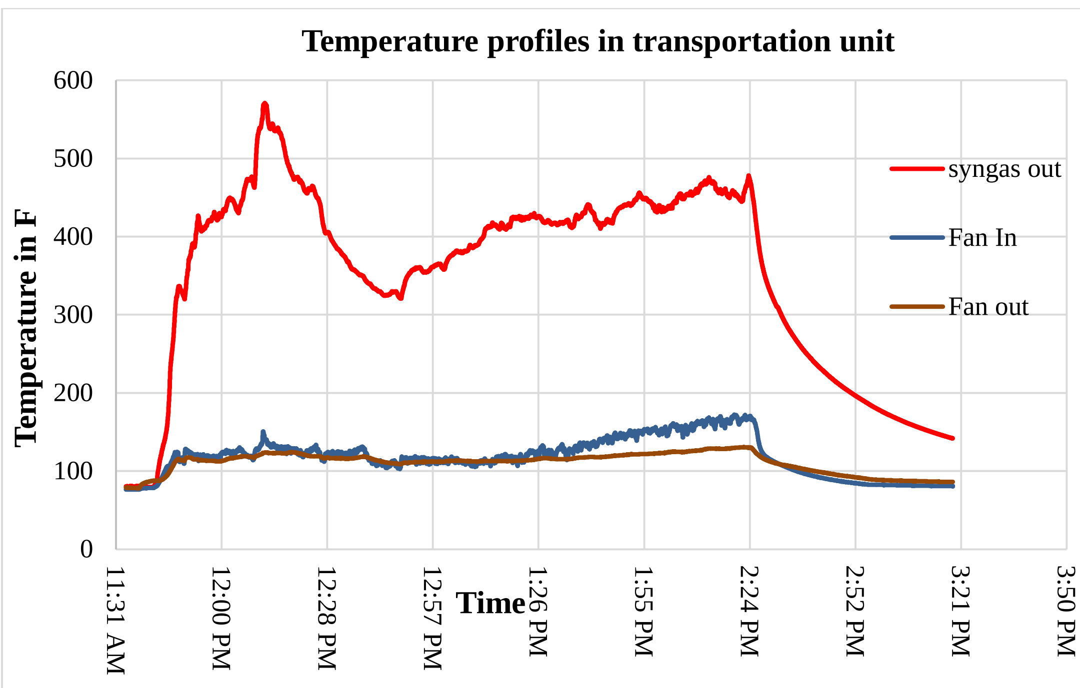


Figure 4.4. Temperature profiles inside condensation unit

Figure 4.5. below shows the syngas and burner oxygen sensors vs time plot. In this, both the syngas and burner oxygen at time till 11:30 am shows the AFR lambda values in sensors to be nearly 8 which is equivalent to 21% of oxygen nearly. When the experiment starts at around 11:30 am, the oxygen values of both the sensors starts to decrease immediately to less than 1% of oxygen concentration in the reactor. These concentration values are always maintained below 1% to ensure that the process is always below UFL of CO and H_2. The values on the oxygen sensors should be less than 1.0 lambda values while running the process, which are with the range of 1% UFL values. These oxygen values also show that there is no leak inside the unit. The oxygen values on the sensor also play a significant role in understanding the process. If the syngas oxygen sensor values are more, it signifies air is not passing through the system which may require to opening a value to increase the flow. If both the oxygen values are low and nearly same signifies no leak inside the system.

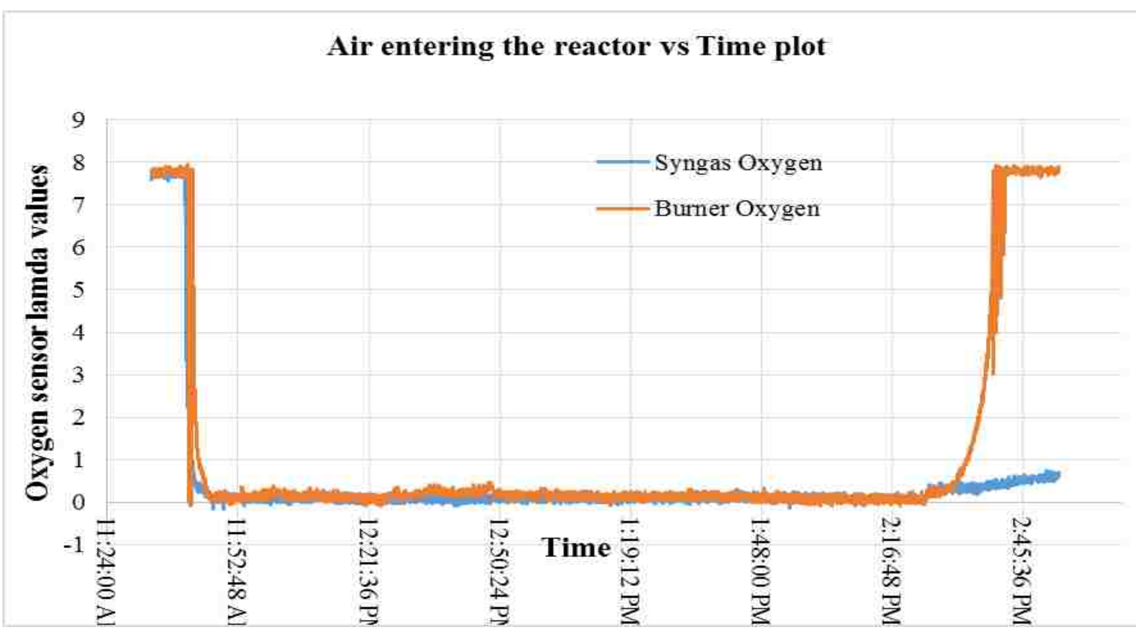


Figure 4.5. Lambda values of oxygen sensors vs time

At 2:24 pm as shown in Figure 4.6., shutdown process was started by removing thermocouples inside the reactor and sealing the reactor with nitrogen purge door. We see there is an immediate drop in temperatures inside the reactor and purge nitrogen until reactions are killed. The induced draft fan is turned off and the upstream valve is opened completely as discussed in the shutdown procedure in the Section 3. The shutdown thermocouple temperatures increase when nitrogen purged door is kept on the top of the reactor, decreases while nitrogen is purged to reactor and increases while nitrogen flow is stopped. After some time the temperatures again starts decreasing to room temperatures as the reactions are killed inside the reactor.

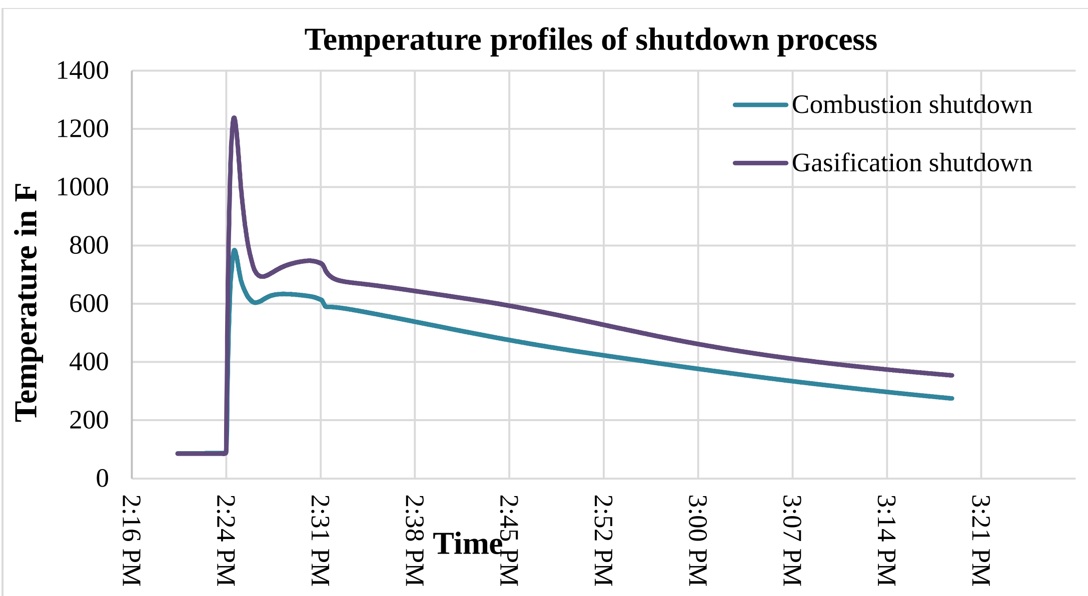


Figure 4.6. Shutdown temperature profiles inside reactor

On doing mass balance for a 4” reactor, the feed rate of pellets was approximately 0.14 lb/min for a steady state process. The products produced chars, bio-oil, ash and syngas contributed to around 7.6%, 3.2% 0.3% and 88.9% respectively of biomass feedstock.

4.2. STEADY STATE PROCESS IN AN 8” REACTOR

The operating procedure for 8” reactor is similar to that of 4” reactor for pellets. Since the biomass fed to the 8” reactor is more, there is a high restriction for air flow for combustion processes. So compared to 4” reactor the valve setting or air flow to the gasifier is more for 8” reactor. Figure 4.7. below shows the temperatures of different zones inside the reactor.

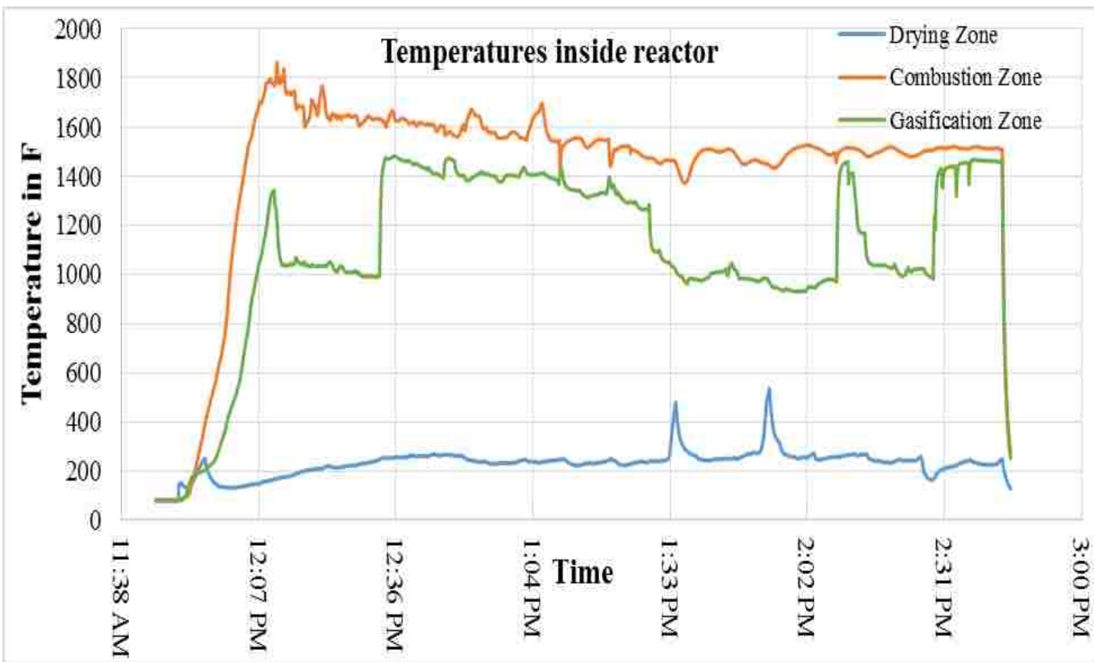


Figure 4.7. Temperatures profiles inside the reactor

From Figure 4.7., the startup process took off at 11:50 am and the oscillations in combustion temperature is due to the addition of feed for the steady state process. For 8” reactor, the extent of longitudinal vibration that should be given to the flange is more compared to 4” because of large bed present inside the reactor. This vibration has caused the gasification thermocouple to move from its position and the drop in gasification zone at times 12:10 pm, 1:30 pm and 2:15 pm is due to misplacement of gasification thermocouple. Also, the upstream ball valve can be opened further which supplies more air for high combustion temperatures leaving high-temperature products thereby increasing the temperatures of syngas outlet which results in sending high-temperature products to induced draft fan as shown in Figure 4.8.

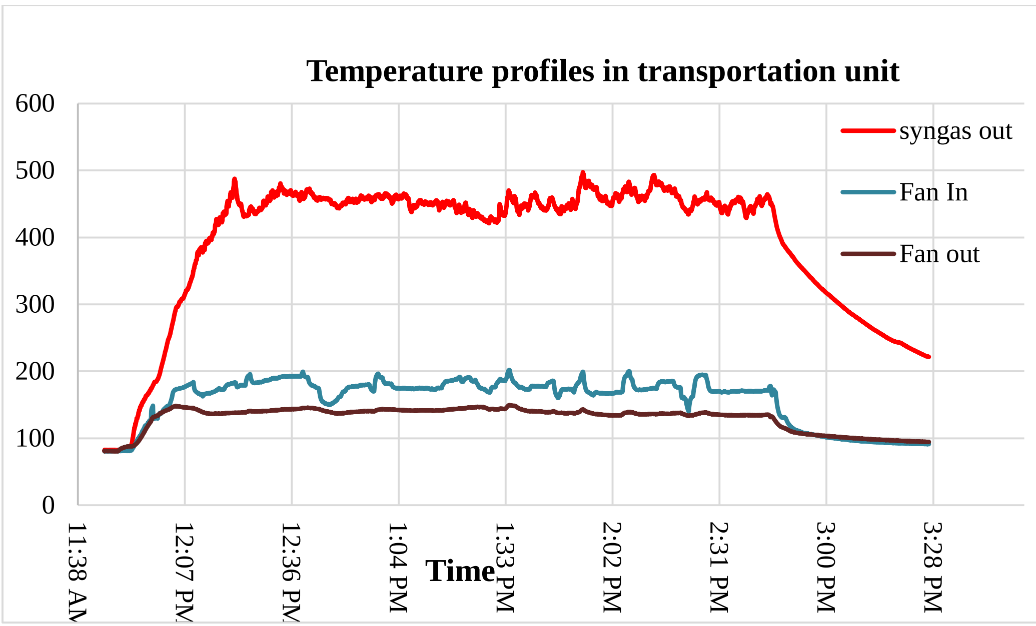


Figure 4.8. Temperatures of condensation unit for 8” reactor.

The Figure 4.8. shows the temperature profiles inside the condensation unit. In this, we see that the temperatures for syngas outlet and fan in temperatures are considerably high compared to that of 4” reactor. This is because, for 8” reactor the air required for combustion process is more which also means the pull of syngas from the reactor is also more. This high production of products is the reason for high-temperature of syngas outlet and takes more time to cool to the same extent as that of the 4” reactor syngas outlet. Another reason for a high temperature of products is a high flow of air to the system to avoid restriction. The syngas flame inside the combustion flare (shown in Figure 4.9.) for 8” reactor is almost two and a half times that of syngas flame in 4” reactor. The shutdown procedure for the 8” reactor needs more nitrogen as the amount of bed inside the reactor is more compared to the 4” reactor.

Figure 4.9. Syngas flame inside the combustion flare for 8” reactor

On doing mass balance for an 8” reactor, the feed rate of pellets was approximately 0.32 lb/min for a steady state process. The products produced chars, bio-oil, ash and syngas contributed to around 11.96%, 4.47% 0.3% and 83.27% of biomass feedstock respectively. This relation of syngas flame height and feed rate for 8” reactor is approximately 2.5 times of 4” reactor. The relation is not directly proportional to volumes of the reactor. The slight variation in the percentages of products formed might be due to limited supply of oxygen for 8” reactor. This lead to improper combustion of feedstocks inside the reactor causing variation from 4” reactor. For better efficiency, it is suggested to have 4 small 4” reactors as it equals 8” reactor volume connected in series than a single 8” reactor. Also, smaller diameter or bed inside the reactors are much easier to control than a single larger bed. But the cons being the cost for 4 inches reactors is more than for single 8” reactor.

4.3. SYNGAS COMPOSITION

The composition of syngas mixture is measured using a gas chromatography which can separate and analyze the components in the mixture without decomposing. The composition of syngas which used air as a gasifying medium is shown in Table 4.1. This syngas produced can be used for many purposes like electricity generation instead of natural gas. This is used to produce steam where the steam passes through turbine to generate power. Other applications of syngas as a crucial intermediate for the production of products like ammonia, hydrogen, methanol and synthetic petroleum etc.

Table 4.1. Syngas composition for pellets

Component	**Volume %**
Hydrogen	18
Carbon monoxide	21
Carbon dioxide	16
Methane	2
C_2^+ hydrocarbons	2
Nitrogen	41

4.4. BIO-OIL

Bio-oil is the complex organic compound which is formed during the pyrolysis of biomass. It is a mixture of aromatics, phenolic, alkenes, furans, esters etc. functional group and significantly high amount of oxygen content. It is high viscous liquid with relatively high water content and low calorific values. It has significant amounts of renewable liquid fuel and has to be upgraded before it can be used as a fuel. Liquid- liquid extraction method is said to have high potential in separating and improving quality of bio-oil into different compounds. The product collected in the first tar collection unit is mostly water whereas the second tar collection unit has much of condensed bio-oil in it. Figure 4.10. below shows bio-oil collected in the second tar collection unit. Like its source, the emissions from bio-oil is said to have less % of CO_2 and SO_2 emissions [18, 28-30].

Figure 4.10. Bio-oil collected from the tar collection valve

5. SIX SIGMA IN PROCESSING DIFFERENT WOODY FEEDSTOCKS

In the previous Sections, we investigated how the size of reactor changes in the operating procedure for gasification process of wood pellets. In the current Section, we study how different wood feed stocks namely pellets, flakes and wood chips (discussed in Section 3) vary in operation for a single size of the reactor (8”). This work focuses on exploring how shape and moisture content in different wood feedstocks, air flow and length of bed inside the reactor makes a difference in the gasification processes. For this, a systematic methodology of Six Sigma’s DMAIC approach was used to analyze the existing biomass gasification process discussed in Section 3. By considering ‘Define’ and ‘Analyze’ phase, this study has validated the importance of Six Sigma in significantly defining the problem of how different types of feedstocks are processed differently dealing with the continuous improvement of the process. In this Section, we will discuss the five phase methodology of Six Sigma known as DMAIC or define-measure-analyze-improve and control approach where the existing process is deeply analyzed for its root causes and effects for processing different woody feedstocks [31-34].

5.1. DEFINE PHASE

The define phase which is the first stage in the Six Sigma analysis is started by writing a project charter. In this phase, the problem and goals of the process are formulated and outlined. As the first step in the define phase, project charter was prepared which gives us an idea of the scope, objectives and helps in focusing on the project with aligned goals. This is the step where the project is well defined and understood for its results and process improvement.

Problem statement: The purpose of this study designs a biomass gasifier and to study how different type of feedstock, variation in air flow to the system makes a difference in the gasification process.

Project goal: The goal of the project is to identify the better type of feedstock among wood chips, flakes and pellets considering its shape and properties. The mean temperatures for gasification and combustion processes have to be increased or high being in their specification limits while for the fan in and syngas outlet it has to be decreased to maintain a proper steady state. Also, a summary of how oxygen levels or air flow to the system effects the gasification process for different feeds and different ball valve settings.

Requirements and Expectations: From this study, we expect the temperature profiles of combustion, gasification, syngas outlet and fan inlet temperatures are within the specification limits and see how they vary for different feedstocks.

In the following steps, we go to DMAIC roadmap, where we initially define the process to understand and analyze the system. To do this, we have to study the design and methodology which are already discussed in Section 2 and Section 3 respectively. After several sessions of brainstorming with research group the design changes and the design itself are presented in a tree diagram for simplifying the system. This tree diagram shown in Figure 5.1. helps us to know and understand all the details in a very small time. Noting and keeping track of all the ideas makes it easier to go back and review which helps in reviewing and remembering some important points which might be forgotten over time and which also helps in focusing on the aim of the project where some tasks might be side tracked over time or the change in ideas. Further, this representation in a tree diagram also saves time in understanding and go through the design.

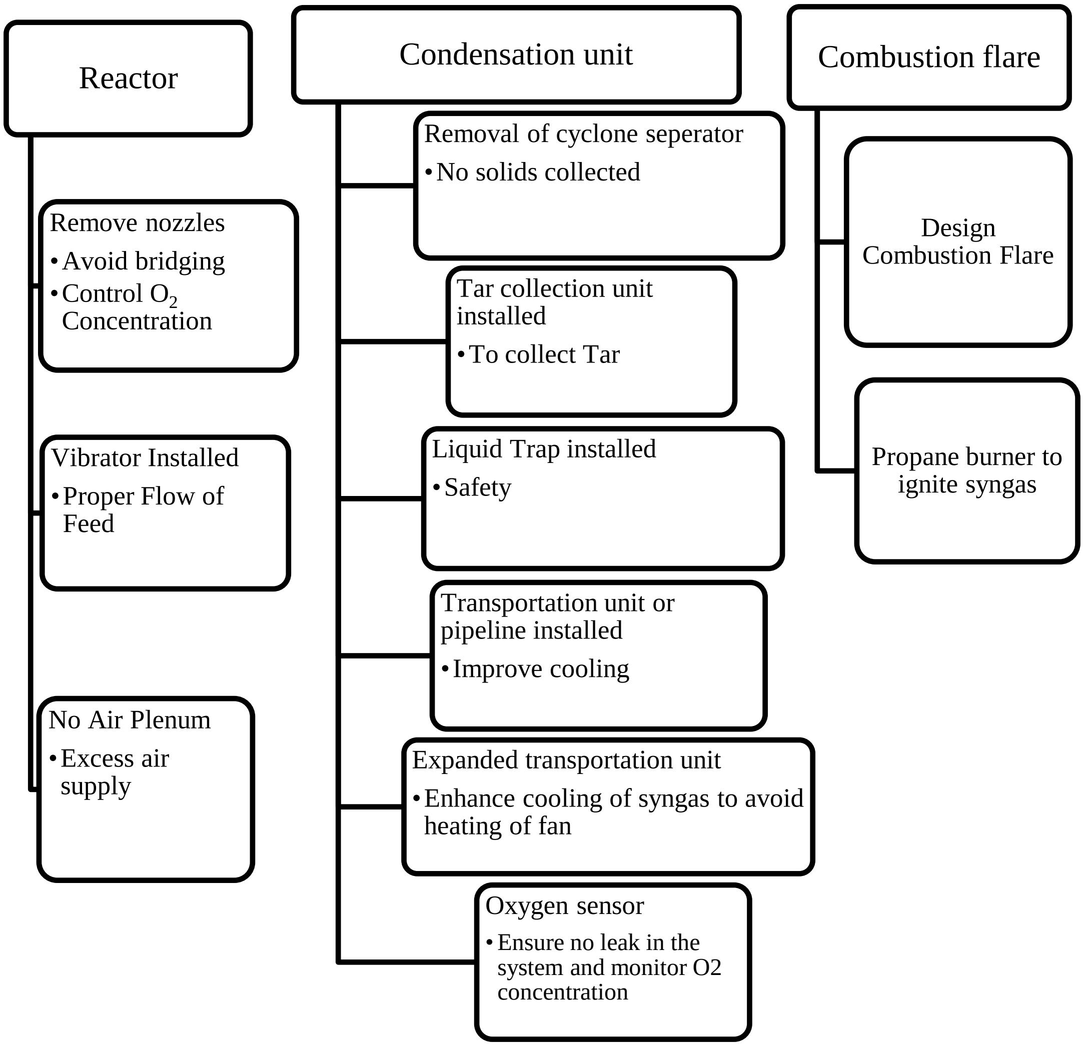


Figure 5.1. Tree diagram of biomass gasifier design and its changes

The next detail in the define phase is the SIPOC diagram (Suppliers, Input, Process, Output, and Customers) which is a tool that can be used by the entire team to identify the scope of work at each level along with the deficiencies between the customer and the process[35]. The SIPOC diagram for Biomass reactor system is shown in Figure 5.2. and is divided into two parts for the startup and the continuous process where all duties that are to be performed during a single step are noted. After the continuous process, the shutdown process is started by purging the nitrogen.

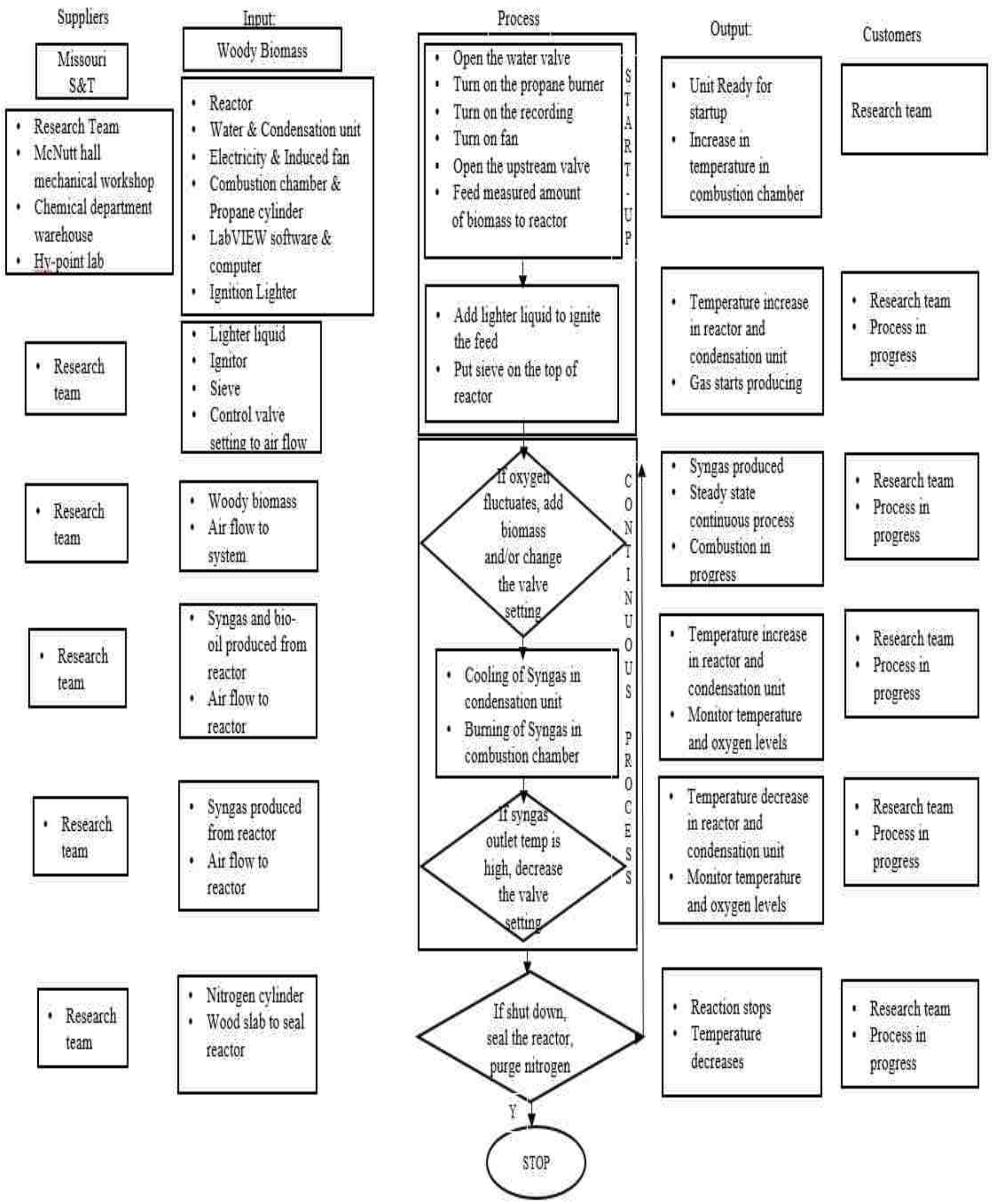


Figure 5.2. SIPOC diagram and Process Flow chart for biomass gasification process

5.2. THE MEASURE PHASE

During the define phase, the design, key process, design changes, input and output variables were identified. Now, in the measure phase, the goal is to address the location or source of problems by establishing an understanding of existing process conditions and problems. The research team started up this study by collecting and analyzing data from LabVIEW, units of measurement and related operating conditions of the process. In this phase, we try to understand the best or easy to process feed type out of wood chips, flakes, and pellets for biomass gasification process. For this purpose, we consider the data collected from wood chips as the baseline data. Wood chips are basically unprocessed woody biomass which has higher moisture content and are brought directly from forests. We take into consideration the operating conditions and temperatures profiles obtained while processing this feed type. This data was collected and analyzed from LabVIEW to evaluate the process performance and to find areas for process and continuous improvement. Out of various data measuring points or spots we take into consideration 4 important temperature zones i.e. combustion, gasification, syngas out and fan in temperatures. The flow of air from ball valve and oxygen concentration for combustion processes are discussed in later parts of the paper. In data collection, combustion and gasification zone temperatures are very much important in a gasification process to continue the steady state and for proper production of the gas. Also, the outlet temperature of the syngas and fan inlet are important as they give us an indication if the length of transportation unit is enough or not for temperatures to fall through convection process. Care has to be taken that hot gas shouldn’t pass through fan inlet as it may lead to burning of the fan in the middle of a process which is a huge safety hazard. So the temperatures of different zones are continuously monitored and controlled based on their upper and lower specification limits for different zones in the system as shown in Table 5.1. below.

Table 5.1. Specification limits of different temperature zones

Zone	Lower Specification Limit (F)	Upper Specification Limit (F)
Combustion temperature	1550	2000
Gasification temperature	1350	1550
Syngas out temperature	As low as possible	450
Fan In temperature	As low as possible	200

This measurement and analysis of temperature profiles are done after the steady state is achieved. At first for the startup process, the feed was added then ignited for the gasification process. The new feed is then added on the top for a limited supply of oxygen and continuous steady state process. The date point in LabVIEW is collected at the interval of every second and since one steady state is considered as the time at which new batch of feed is added to the reactor to which another batch is added. So we get a huge number of data points for one steady state process and the easiest way to analyze and understand all this data was to plot in histograms. Histograms are the graphical representation of data where the data points collected are spread in the different frequency range to see the concentration of data points. For the data points obtained in the experiment the temperature zones are divided to different frequencies and their concentration is known for their spread for each zone. Also, we take into account the lower and upper specification limits and see if the data obtained is how near to the desired values. The histograms in Figure 5.3., Figure 5.4., Figure 5.5., and Figure 5.6., show the spread of combustion, gasification, syngas out and fan in temperatures for the baseline data i.e. steady state process of wood chips.

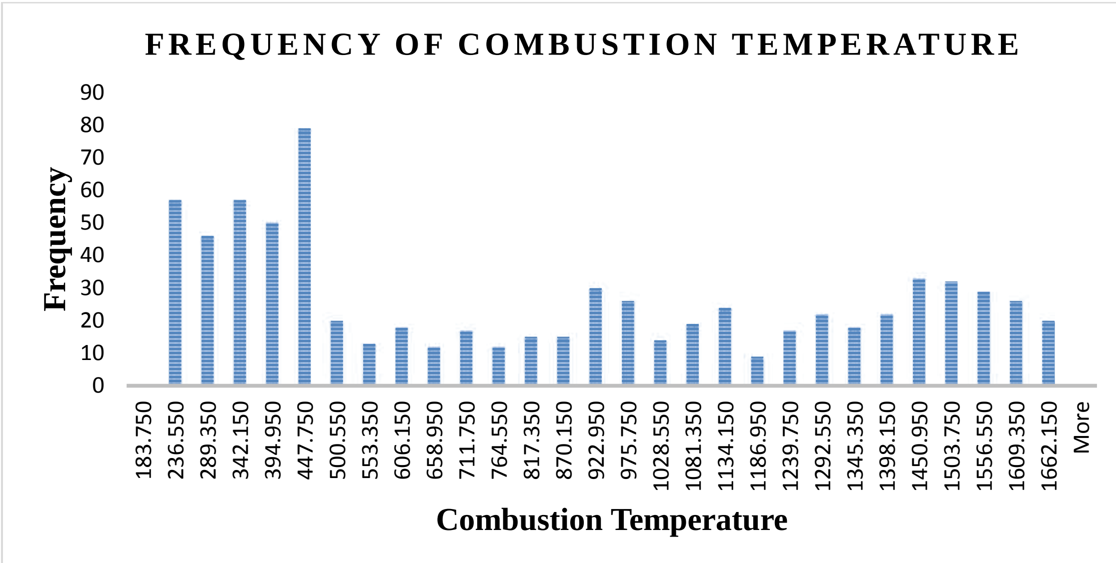


Figure 5.3. Histogram of combustion temperature for wood chips

As we know wood chips are basically unprocessed biomass and has the relatively high amount of moisture in it. A new batch of feed is added when we see a burning charcoal in the reactor from the top where the combustion thermocouple is placed. So whenever a new batch of feed is added for a continuous steady state process, due to its high moisture content, temperatures inside the reactor rapidly fall for combustion zone which is far away from its specification limits. For chips, as shown in Figure 5.3, we see more data points are concentrated in lower temperature regions than that of combustion specifications as it takes the time to process and loose the moisture content in feed and this histogram is skewed towards left. So for woodchips, we need to make sure limited amounts of feed is added for steady state as excess feed increases moisture contents inside the reactor and may lead to loosing of the burning bed.

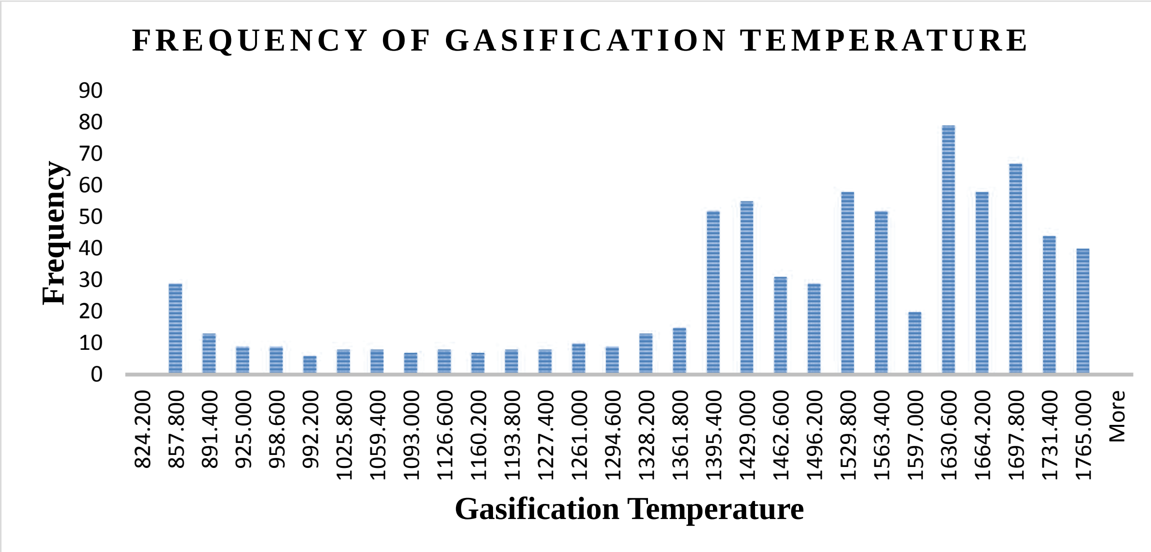


Figure 5.4. Histogram of gasification temperature for wood chips

In Figure 5.4, the spread of gasification temperature for wood chips is shown where we again notice much data is concentrated out of specification zones. This is because the air flow was increased to support combustion process in avoiding loosing of bed, which led to moving the bed downwards and increase the temperature of gasification zone. This increase in temperature of gasification zone is not desirable as there is a chance that the feed is not gasifying but it’s just combusting due to an excess supply of air. Figure 5.5, shows the histogram of syngas outlet temperatures and we could see almost even spread of data except for the small range of temperatures. These values are much higher than the desirable range but it is again due to increase in air flow which leads to combustion and release of high-temperature gas/smoke from the bottom of the reactor. Figure 5.6. shows the spread of fan inlet temperatures, these values are towards the high end of the specification limit due to high air flow and increase in temperatures at the bottom of the reactor.

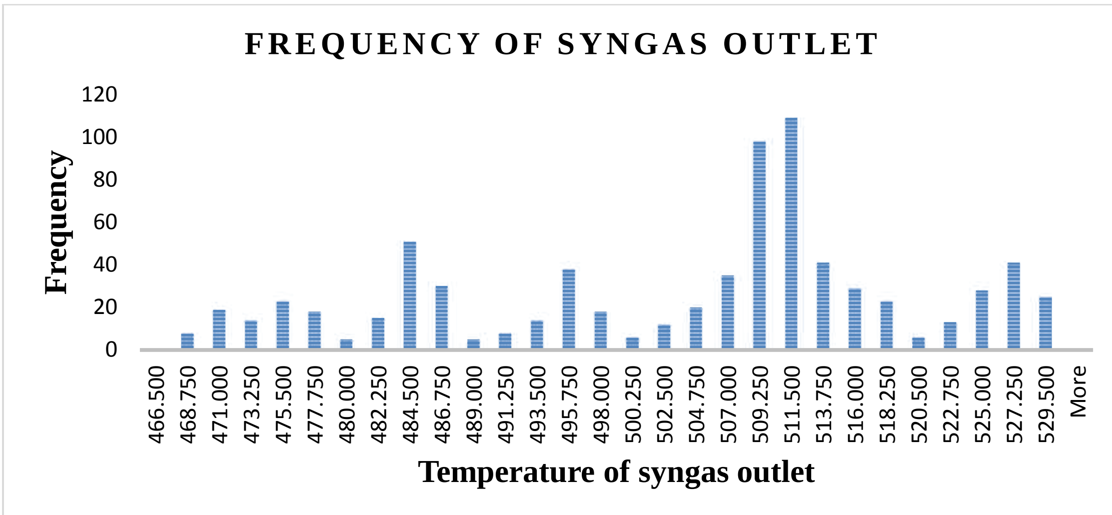


Figure 5.5. Histogram of syngas outlet temperature for wood chips

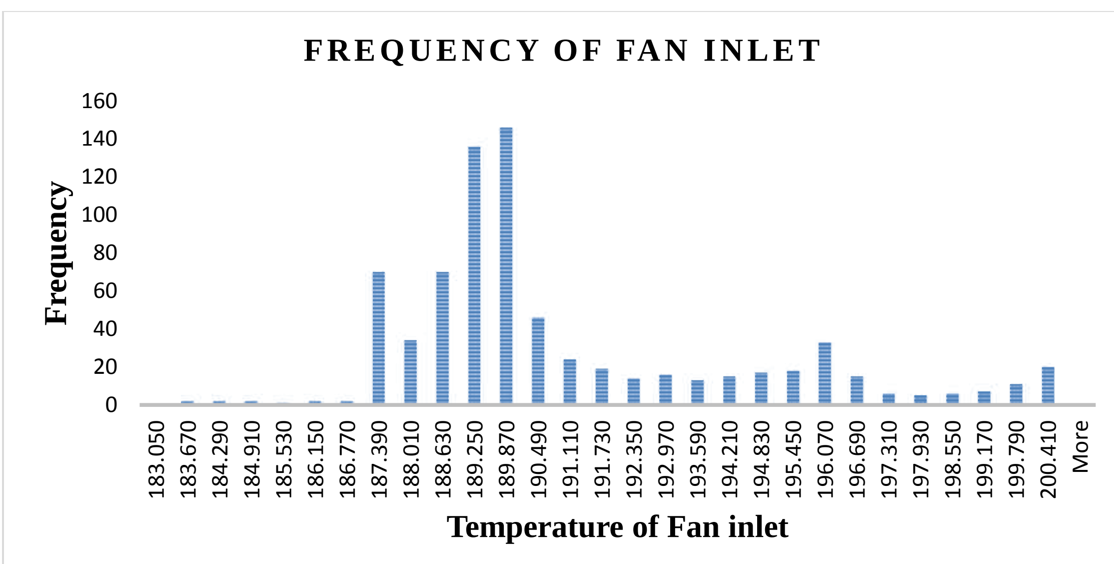


Figure 5.6. Histogram of fan in temperature for wood chips

From the histograms above, we see the spread of combustion, gasification, syngas outlet and fan inlet temperatures for our baseline data or wood chips. As a conclusion, we see the reasons behind obtaining this spread for baseline data. We see a decent amount of combustion temperature data was below specification limits due to high moisture content of the feed, and to increase combustion we also increase in the flow of air. This increase in oxygen concentration or flow of air moves the bed downwards resulting in an increase in temperatures of gasification zone, syngas out and fan in temperatures. High temperatures in gasification zone are not desirable as there might be combusting happening instead of gasifying, also with high syngas out and fan in temperatures there is a risk of burning the fan in the middle of the process. In further study, we use different statistical techniques to find the exact measurement characteristics which are summarized as below in Table 5.2.

Table 5.2. Baseline data parameters

	Combustion	Gasification	Syngas out	Fan In
Mean	811.689	1458.47	502.607	190.71
Standard Deviation	476.06	245.17	16.277	3.41

From the baseline data Table 5.2, we see that the mean temperatures are not within the desired specification limits, and thus the main aim of this study is to see which type of feed has the process temperatures within or near to the specification limits and to maintain the process stability. Apart from the means we calculate and see the standard deviations of all four temperatures zones are large and target to reduce the standard deviation of the processes. In the next step, we proceed to the analyze phase of the project to see what are the major factors that's are influencing in obtaining the results.

5.3. THE ANALYZE PHASE

After completing the measured phase on the DMAIC roadmap for this study, we now move on to analyzing the data. As we concluded in the measured phase, the mean temperatures has to fall within the specification limits and reduce the standard deviation. In this phase, we identify root causes of problems in the process and validate these causes. This is done using a Cause and Effect Diagram, or Fishbone diagram which helps us in discovering all the possible causes for a particular effect as shown in Figure 5.7.

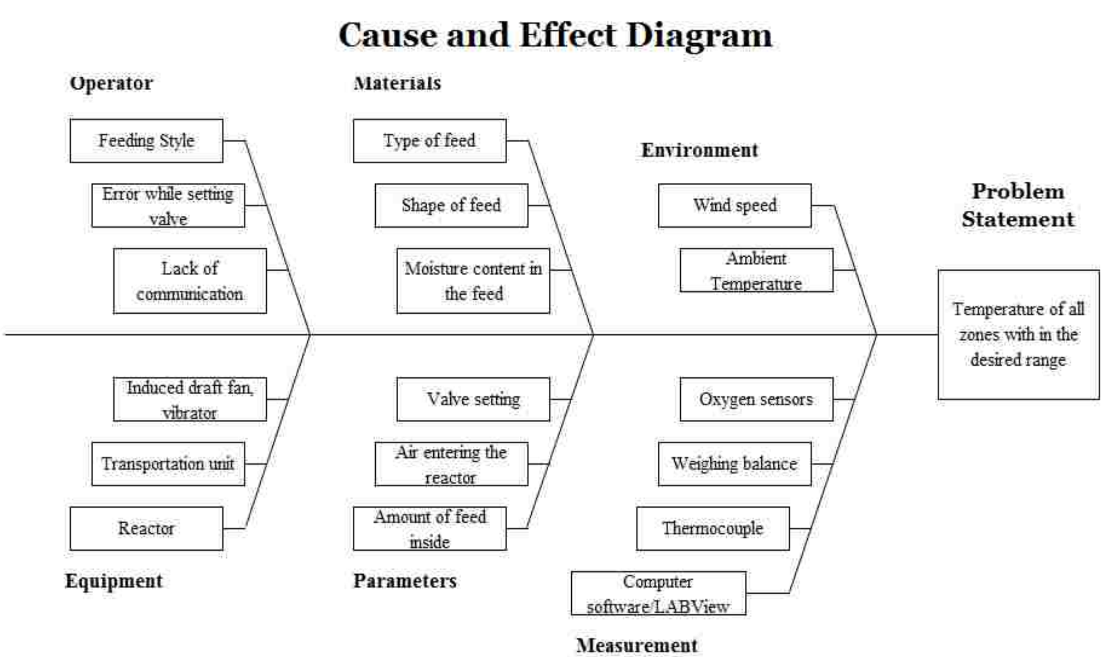


Figure 5.7. Fishbone diagram for causes and effects in biomass gasification process

This analysis is done after conducting a brainstorming session with the research team, people involved in the process along with the experts. After detailed discussion and study of gathered data a list of potential causes and their effects are taken in a CE diagram. The cause and effect diagram considers the following factors to find out process variation – Man, Material, Environment, Equipment, Parameters and Measurement. From this, we can see what are the parameters that are controlled and which are not in our control. Some of these causes includes detailed data gathering from LabVIEW and study statistical analysis to validate the potential causes. Figure 5.7. above shows the Cause and Effect diagram considering different parameters in a biomass gasification process for our designed reactor.

As per the cause and effect diagram we see the type of feed plays an important role for the gasification process. So by taking different feed stocks we see if the biomass gasification process is happening in a way that is desired. For these two feedstocks we see if the mean temperatures of different zones are within or near the specifications limits or not. In order to check if the mean temperatures had actually changed and improved from the base line study, we performed hypothesis tests to see if the process was now performing as per our requirements and to see if type of feed, which is a factor mentioned in the cause and effect diagram plays a significant role in process improvement. As we have four temperatures to monitor, we perform four hypothesis tests; one for each temperature zone i.e. combustion zone, gasification zone, syngas out and fan inlet temperature. For the Combustion and Gasification temperatures, we want the mean temperature to increase as our baseline data is below the specification limits. For Syngas out and Fan In temperatures, the baseline mean temperatures are above or to the top end of specification limits, so we want the mean temperatures for these feedstocks to decrease. Hypothesis testing is defined as the statistical hypothesis where we check probability of determining, if the defined hypothesis is true. In hypothesis testing the actual hypothesis i.e. to be tested consists of two complementary statements about the actual state of the nature. In this, α or error value is depending upon the criticality of the process and its Z confidence levels are taken from the standard normal probabilities table in appendix. The hypothesis test performed our data to check temperatures of each zone for different feedstocks is the two population test, which compares mean temperatures of two populations. The formula used for this test is as follows.

Here $\left(\overline{X}_1 - \overline{X}_2\right)$ are the difference in means of assumed hypothesis

(μ1 - μ2) are the actual hypothesis mean difference

σ_1^2 , σ_2^2 are the squares of standard deviation and

n_1 and n_2 are the number of data points for baseline data and tested data respectively.

$$Z_0 = \frac{\left(\overline{X}_1 - \overline{X}_2\right) - (\mu_1 - \mu_2)}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

This formula is used as we have a different number of data points for baseline data and for new feedstocks and different mean, the standard deviation for different feedstocks. There are two types of feed and four hypothesis test for each zones, i.e. combustion, gasification, syngas outlet and fan inlet temperature are shown in Table 5.3. below with a brief summary of the results. For all the hypothesis test α value was considered as 0.05 or 5% critical error.

Table 5.3. Hypothesis test for feed type - Flakes

	Combustion Temp	Gasification	Syngas Out	Fan In
Zo	2.029	-0.103	-110.734	15.030
Result	Reject	Fail to Reject	Reject	Fail to Reject
Remarks	The mean temperature of combustion for flakes and baseline data are different	The mean temperature of gasification of flakes and is same as baseline	The mean temperature of syngas out has decreased	The mean temperature of fan inlet is same as baseline

For other feed type flakes, the hypothesis test conducted gave us the desired results for the combustion and gasification zones, i.e. mean for combustion zone has increased and that for gasification zone having not changed from baseline. Since in baseline data, the mean temperatures were already within the specification limit but the problem was much data in the gasification zone has higher temperatures than the desired values because of the excess air sent to the system and combustion happening instead of gasification. In hypothesis test of syngas out temperature, we see that the mean values have decreased to desired range. But for the fan in temperature, the hypothesis test result has Fail to reject the hypothesis, as there is no decrease in mean temperatures of this zone. From the null hypothesis, the hypothesis is never accepted, it is either rejected or not rejected.

From the result of a hypothesis test for pellets shown in Table 5.4., we see that the combustion zone mean temperature has increased to considerably the desired result. The gasification zone temperature was already in the specified limits, hypothesis test shows that the mean hasn't changed much and also shows most data concentration is within the specification limits. Also, as per hypothesis testing the syngas out and Fan in mean temperatures have reduced drastically, which was the desired result. This also proves that the type of feed in cause and effect diagram is one of the important factor for gasification process.

Table 5.4. Hypothesis test for feed type - Pellets

	Combustion	Gasification	Syngas Out	Fan In
Zo	2.58	0.287	-298.14	-1214.396
Test Result	Reject	Fail to Reject	Reject	Reject
Remarks	The mean temperature of combustion has increased	The mean temperature of gasification is same as baseline	The mean temperature of syngas out has decreased	The mean Fan In temperature has decreased

5.4. IMPROVE AND CONTROL PHASE

The objective of this phase is to find solutions for the root causes in the project and to implement and observe solutions validate the process. On the basis of brainstorming session conducted by the research team and all the people involved in the process, the team used the failure mode and effect analysis (FMEA) to understand the process. This tool helped us to identify the potential failures which are associated with our action on the gasification process. Since our study involves a continuous steady state biomass gasification process for different types of feed, there are a lot of factors such as the amount of the feed and air sent to the reactor, opening and closing of the ball valve for airflow, shape and transportability of feed are considered for a deep understanding of FMEA. There are two types of FMEA, first, includes FMEA in the process operation and other due to unexpected incidents that can happen to the system. In this study, we only include FMEA that is caused while operating the process. After deep understanding of the process, we selected three important factors which are affecting the process on a high scale of severity. These factors were types of the feed, amount of the feed and concentration of oxygen/air sent to the reactor. The analysis is done on the basis of the risk priority number (RPN). For FMEA, we see severity, occurrence, detection and RPN values for the process and undertake actions to maintain a stable steady and low RPN values which signify failure. The Table 5.5. below gives the list of RPN values range i.e. it defines the numbers vary in each severity, occurrence, and detection from a lower range to upper range. Severity is defined on the scale from minor on the low scale and catastrophic on the high scale. For severity, the lower values are minor or 1 which means the effect by this FMEA is not much but when the values are nearer to 10 shows the impact is much more severe and considered as a life or environmental hazard. The occurrence is used to know the frequency of the event to be happening. The scale of the occurrence ranges from remote on the low scale and definite on the high scale. Detection column shows the ability to detect the failure at that process step. For detection, it is stated from 1 as high easily detected to 10 as nil- not detectable. Not being able to detect any change is considered as a serious issue and is given high RPN number. For any process, the high-end FMEA values which are considered to be hazardous in operation are to be decreased to lower values.

Table 5.5. Range of RPN values from low to top

Severity	Occurrence	Detection
10: Catastrophic	10: Definite	10: Nil- Not detectable at all
7: Critical	7: Occasional	7: Low
4: Serious	4: Few	4: Medium
1: Minor	1: Remote	1: Highly detected

In our investigation of steady state biomass gasification process for different feedstocks, the first FMEA factor is the type of feed where we take into consideration its moisture content and effect of the shape of feed. For the gasification reactions to happen smoothly moisture content and transportability of feed in the reactor plays a very important role. High moisture content leads to decrease in temperatures of combustion and gasification zones and may eventually cause in losing of bed whereas the uneven shape of feed creates some air gaps/voids inside the reactor while processing. In FMEA Table 5.6. below, pellets which are processed biomass feedstock coming from industry has less moisture content and are evenly shaped. So they don't have high values in the criticality of RPN number. These effects inside the reactor are detected on LabVIEW and void inside the reactor are detected when manual tapping of the reactor is made. To reduce the criticality for moisture content and uneven transportability of feed, the feed is pre-dried and a strong vibrator is installed for having a uniform movement of combustion bed across the cross section. Chips are the unprocessed feedstocks coming directly from the forest and has a moisture content nearly up to 35% and are irregular in shape. The effect of this FMEA is considerably very high for picks than for pellets. For flakes, it follows same trend that of wood chips in terms of transportability. Since picks have high moisture content and are irregular in shape, it has high RPN values the value decreases considerably after implementing the actions.

Table 5.6. FEMA of gasification process for different feed types

		Potential Failure mode			Criticality						Criticality			
step	Function	Type	Cause	Effect	S	O	D	RPN	Detection	Action	S	O	D	RPN
Feed Type	Burns to produce gas	Pellets	moisture	Resistance to burn	1	1	1	1	LabVIEW	Pre-drying	1	1	1	1
			shape	Uneven transport of feed	3	3	1	9	Visual	Use of vibrator	1	1	1	1
		Chips	moisture	Resistance to burn	4	7	4	112	LabVIEW	Pre-drying	1	4	1	4
			shape	Uneven transport of feed	7	7	7	343	Visual	Use of vibrator	4	4	4	64
		Flakes	moisture	Resistance to burn	4	1	1	4	LabVIEW	Pre-drying	1	1	1	1
			shape	Uneven transport of feed	4	4	7	112	Visual	Use of vibrator	4	4	4	64

The second mode of failure in this process is the rate of feed. The amount of feed added to the reactor play a very important role in maintaining the steady state process. If high feed rate is added to the reactor then there is a high restriction for the flow of air to undergo combustion processes inside the reactor. For pellets, since they are denser and evenly shaped small batches of feed are fed to avoid restriction of air flow to the system. The quality and density of syngas flame in combustion flare also depends on how much air is sent to the system as combustion and gasification temperatures are dependent on it. For wood chips, a small rate of feedstock is fed to the reactor for two reasons one being a restriction of air flow and other, the high moisture content of feed increases moisture inside the bed thereby resulting in loosing of combustion and gasification bed. This is detected by thermocouples connected to LabVIEW and by seeing syngas flame in combustion flare. As the new feed is fed to the reactor, the temperatures inside the reactor start decreasing due to room temperature of feed. If this temperature decreases drastically then there is a chance of losing the bed. So smaller rates of feed make sure the temperature increases back to the desired temperatures in some time. Very less feed rate might also take up high air flow to the system resulting only in combustion process instead of gasification. Because of this low feed rate and high oxygen concentration, the combustion bed also moves down which results in leaving high-temperature products. This high temperature for products are not desirable for fan inlet as this leading to burning of fan blades and disturb the whole process in between the experiment which is an experimental hazard. So there should be the optimum flow rate of feed to maintain a steady state process. Table 5.7. below shows the FMEA process for feed rate in the gasification process for three types of feed. In this again, all the RPN values and its lower and upper levels are calculated based on Table 5.5.

Table 5.7. FEMA for feed rate in gasification process

		Potential Failure mode			Criticality						Criticality			
Step	Function	Type	Cause	Effect	S	O	D	RPN	Detection	Action	S	O	D	RPN
Amount of feed	Feed rate	Pellets	High	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	1	1	4	4
			Low	Excess Combustion	7	1	4	28	LabVIEW, O_2 Sensor	Decrease valve	1	1	4	4
		Chips	High	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	4	1	4	16
			Low	Excess Combustion	7	1	4	28	LabVIEW, O_2 Sensor	Decrease valve	4	1	4	1
		Flakes	High	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	4	1	4	16
			Low	Excess Combustion	7	1	4	28	LabVIEW, O_2 Sensor	Decrease valve	4	1	4	1

The other mode of failure related to the operation of the process is a flow of air to the system which is controlled by an upstream ball valve. If the valve is opened more, it takes high air flow to the system which results in moving the bed down towards the grate thereby leaving no much gap between combustion and gasification zones. In doing this, there is a possibility that gasification zone undergoing combustion process which leaves behind smoke instead of gas from the reactor. This high airflow also releases high temperatures products from the bottom which are not desirable due to the burning of a fan with a high fan in temperature. Low flow of air or low valve settings allows limited amount of air to pass through the system. This results in moving the combustion bed which may result in losing of bed and piling of reactor gradually. So optimum air flow is important to the process to maintain a steady state process. Pellets need more air flow as they are much denser and have a high restriction for air flow inside the reactor whereas wood chips and flakes are not denser but need much air flow because of its relatively high moisture content and support combustion process. In Table 5.8., the potential mode of failures of air flow in the biomass gasification process has been discussed.

Table 5.8. FEMA table for flow of air in gasification process

		Potential Failure mode			Criticality						Criticality			
Step	Function	Type	Cause	Effect	S	O	D	RPN	Detection	Action	S	O	D	RPN
Air flow	Valve setting	Pellets	High	Low gasification	7	1	4	28	LabVIEW, O_2 Sensor	Decrease va lve	1	1	4	4
			Low	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	1	1	4	4
		Chips	High	Low gasification	7	1	4	28	LabVIEW, O_2 Sensor	Decrease valve	4	1	4	16
			Low	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	4	1	4	1
		Flakes	High	Low gasification	7	1	4	28	LabVIEW, O_2 Sensor	Decrease valve	4	1	4	16
			Low	Losing of combustion bed	7	1	4	28	LabVIEW, O_2 Sensor	Increase valve	4	1	4	1

The above three FMEA steps are the three potential causes that may happen in the operation of the process. The type of feed, its properties, the amount of air flow and mass feed rate play an important role in maintaining the steady state gasification process. The criticality of this process gives us the better understanding of the process and brainstorming sessions with research team and experts help in reducing the RPN numbers significantly.

5.4.1. Process Improvement by Using Flakes. In the earlier step, we considered wood chips as our baseline data. Now we study the operating procedure for pellets and flakes for design improvement. As the first step in design improvement, we consider flakes as our first design. As discussed before, flakes are woody feedstocks having relatively less moisture content than wood chips. Because of low moisture content, the combustion and gasification temperatures are well within the specification limits for the process and because of less density the air pull from the atmosphere is also more. In the Table 5.8., it is observed that there is a very significant improvement in the mean temperature of the data which is around 88% for the combustion zone compared to picks. For the baseline data, the mean temperature was 811.689^{o}F, which was way behind the specification limits of 1550-2000^{o}F. But by using the flakes we observed through our calculations that mean value for combustion to be 1523.78^{o}F which is very near to the specification limits. Also, we can see there is a vast decrease in the standard deviation which is nearly 75% but these values of standard deviation are still high and the reason being a low density of flakes causes high air flow creating air voids in the reactor. Because of this, there is sudden decrease and increase in temperatures for combustion zone. The same trend is observed for the gasification zone for flakes, here the mean temperature for gasification was already in specification limits for baseline data too but there is an appreciable percentage of improvement in standard deviation (nearly 43%) which tells us there is a decrease in the variation of temperatures in the gasification zone.

Other important factors that are considered are how the syngas out and fan in temperatures vary with the operation of flakes inside the reactor. From baseline data, we can see that the mean of syngas out and fan in are well above the specification limits which is 300-450 ^{o}F because of high air flow to the system to support combustion from the moisture content of chips. But for flakes, since they contain less moisture and create air gaps because of low density it doesn’t need much air to process and these mean temperatures are well in the range of specification limits. This is a good indication of the improvement in the process i.e. use of flakes is much little easy to operate than wood chips. The variation of this process also decreased which can be seen from the decrease in standard deviation values. For fan-in temperature, we can see both the baseline and flakes design are at the higher end of specification limits. This is because as flakes and chips being less dense creating air voids inside the system the hot air passing through it is easy and doesn’t lose much temperature which coming out of the bed to the fan inlet.

5.4.2. Process Improvement by Pellets. In the later part of design improvement, another change that was made was to use wood pellets for the gasification process. As discussed before, pellets are the processed feed with less moisture content ad are evenly shaped. For pellets, we see all the mean temperatures i.e. combustion, gasification, syngas out and fan inlet temperatures are within the specification limits. From calculations in Table 5.9., we observed that the temperatures are in specification limits and the standard deviation of combustion temperature for pellets reduced by 96%. This shows that pellets not only has all the temperatures in specification limits but also reduced the variations in the system. The same trend is observed for gasification, syngas out and fan in temperatures. For pellets, there is a large combustion and gasification bed present above the grate which is denser than the bed of flakes and chips. So the products formed to leave the thick bed of charcoal at the bottom losing considerable temperature while passing through it than for flakes and chips. This explains why the fan in temperature mean decreased to a large extent thereby making the design best for this process.

Table 5.9. Comparison of mean temperatures for different feed types

Design type	Tool used	Combustion	Gasification	Syngas out	Fan-In
Baseline	Mean	811.689	1458.47	502.607	190.71
	Std. Dev.	476.06	245.17	16.277	3.41
Flakes	Mean	1523.78	1443.36	397.38	191.61
	Std. Dev.	121.86	140.92	13.39	3.66
Pellets	Mean	1590.72	1481.55	367.94	143.18
	Std. Dev.	20.93	19.7	8.82	4.3

5.4.3. Kaizen and 5S. Six Sigma methodology helps us in understanding and implementing the process in a better way to reduce effects and energy consumption. This helped us to increase the efficiency of the process in terms of time, money, reduce energy through movement to implementing 5S technology by sorting the whole work unit with proper instructions and signs. This idea of kaizen not only improves the efficiency of the current system but also changes the environmental conditions of the surroundings.

6. NUMERICAL SIMULATION OF BIOMASS GASIFIER

Computational fluid dynamics is a branch of fluid mechanics which provides of qualitative and quantitative prediction of fluid by means of mathematical modelling, numerical methods and software tools. Due to increase in computer power, advances in numerical techniques, modelling and simulation, the CFD becomes a reality for optimizing the biomass gasifier design and its operation. In this study the software used is Star CCM+ for the modelling of gasifier[36, 37]. Discrete element method is used in this simulation to study the particle behavior of biomass feedstock. The Main objective is to use a comprehensive numerical method to investigate the downdraft biomass gasifier with the particular goal of demonstrating a reliable computational model for gasification and thereby benefitting the understanding of thermal flow and gasification process.

6.1. CAD MODEL AND MESH

Star CCM+ 11.02.010 was used for doing this simulation. The design of the reactor is same as that of the experimental model. The height of the reactor core inside is of 19” and 8” in diameter. The diameter of the syngas plenum is 20” and height is 36” until the loft at the bottom. Syngas outlet is at 4.5” from the top of the reactor. Sieve is at the bottom of the reactor core i.e. at 19” from the top. Star CCM+ is a 3D based tool where much of the options are for surface and volume selections. To have a 2D model in Star, all the individual parts are done on 2D to have a planar surface on $z = 0$ plane where it can be revolved or extruded. This 2D geometry is approximated to 3D where the badge for 2D option is present to mark the perimeters as 2D boundaries as shown in Figure 6.1. Automated 2D mesh is shown in Figure 6.2. which has 6609 cells and 18303 faces.

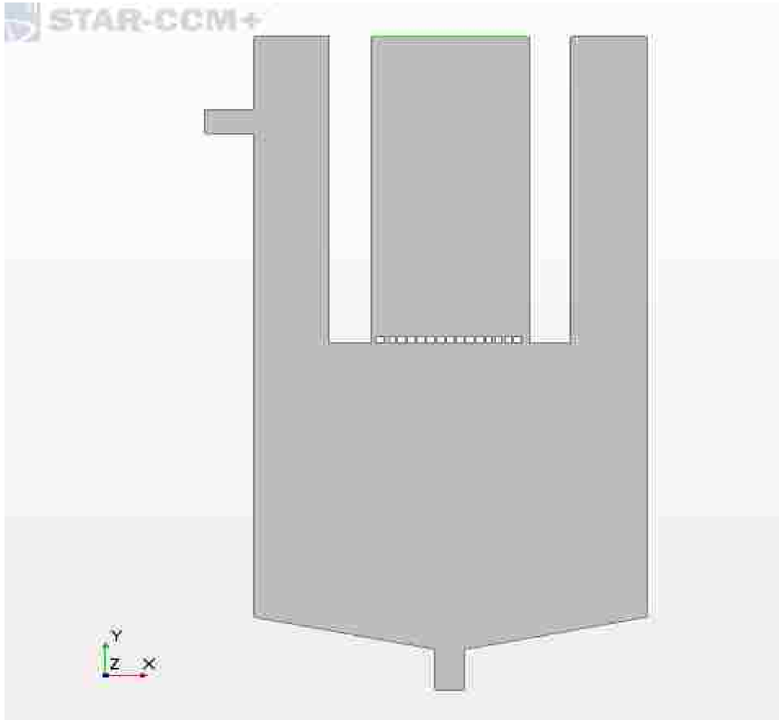


Figure 6.1. CAD model of the biomass gasifier

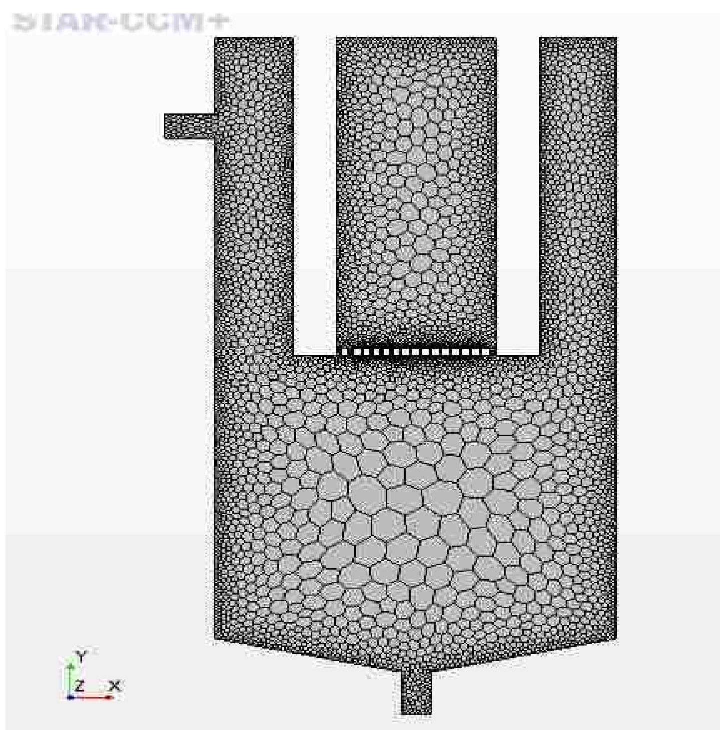


Figure 6.2. Mesh of the biomass gasifier

6.2. MODEL AND SETUP

In this modelling discrete element method is used to accurately reproduce the particle behavior in manufacturing processes. It is a discrete object which can interact with itself and also the geometry. Since it deals with large number of particles DEM model is generally CPU intensive. This method is basically integrating equations of motions which is basically lagrangian based method. Since the biomass feedstock that are used are like granular particles, Lagragian model DEM method is used for this simulation. The advantage in using the DEM model is there is no constitutive required to describe the state of the bulk[37]. The discrete nature of the material can be described explicitly by mentioning the micro properties of the compound. This DEM also considers jamming of particles and forced chains created for granular flow of particles. In this modelling two way coupling to used where particles contribute back to momentum and energy sources[37]. In coupling the two forces considered are buoyancy which is the pressure force on the surface and the drag coefficient. In regions the biomass inlet, syngas outlet, bottom solid outlet are given as the boundary conditions.

The particles shape that is used for simulation is spherical particles where rosin-rammler distribution is used for the diameter of particles. The type of particle injection used was part injector. While injecting the particles in the lagrangian phase the phase 1 or gaseous phase is used. In this modelling two phases are considered, the gaseous and solid phase. In gaseous phase the volatile matter also comes into consideration apart from the product gases formed. The formula of biomass volatiles written from the ultimate and proximate analysis of the biomass composition. While injecting the particles the moisture content, volatile, char and ash are given along with the diameter and temperature of the particle. The volatile formula for all three types of feed is $C_1H_{1.8322}O_{0.9266}N_{0.0014}$, $C_1H_{2.278}O_{1.079}N_{0.007}$ and $C_1H_{1.8626}O_{0.95}N_{0.0014}$ for pellets, chips and flakes respectively. At first by considering all the boundary conditions as wall other than the biomass inlet which is considered as flow split outlet to inject and fill the biomass particles inside the reactor as shown in Figure 6.3. After attaining the desired length the particles injection is stopped and boundary conditions are taken as pressure outlet for syngas outlet and velocity inlet for biomass inlet where the air is entered. The first volatile break up reaction is considered as the eddy break up reaction as the reaction kinetics are unknown. The rest of the models considered are combustion modelling, non-premixed modelling where the char oxidation reactions are included for the biomass gasification process.

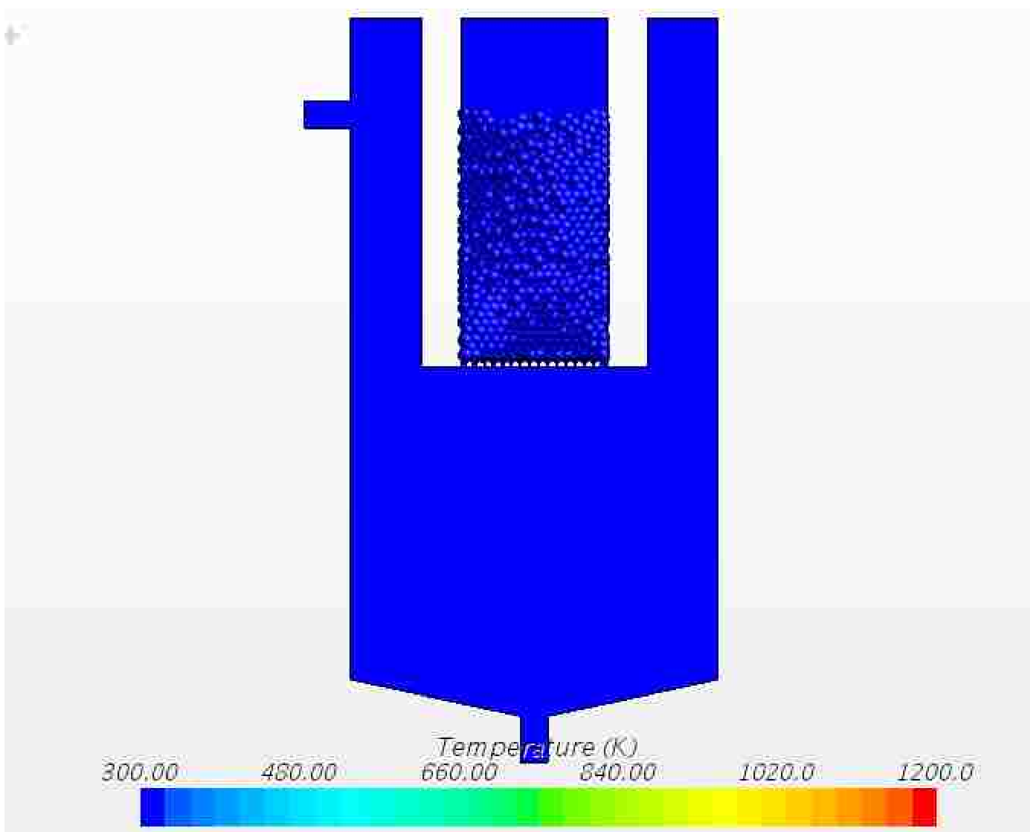


Figure 6.3. Figure showing biomass particles inside the reactor

Once the boundary conditions are set the initial conditions for the model is given as the composition of air for species mass fraction, and a field function is written for the initial temperature. Once the initial and boundary conditions are given the time step and solution methods are selected for the execution of the simulation. For the current set-up the results have been not obtained yet. Further work has to be done to get the reactions happening in the proper way near to the experimental model. For the future work the proper initial and boundary conditions are given to undergo the modelling correctly. This correct prediction of the model also gives us the understanding of the change in process with change in shape, properties and conditions for different feed stocks. This computational fluid dynamic modelling is very helpful in understanding the process by reducing the costs as actual building of the reactor is avoided when some parameters has to be changed and instead can be implemented in CFD model.

7. CONCLUSIONS AND FUTURE WORK

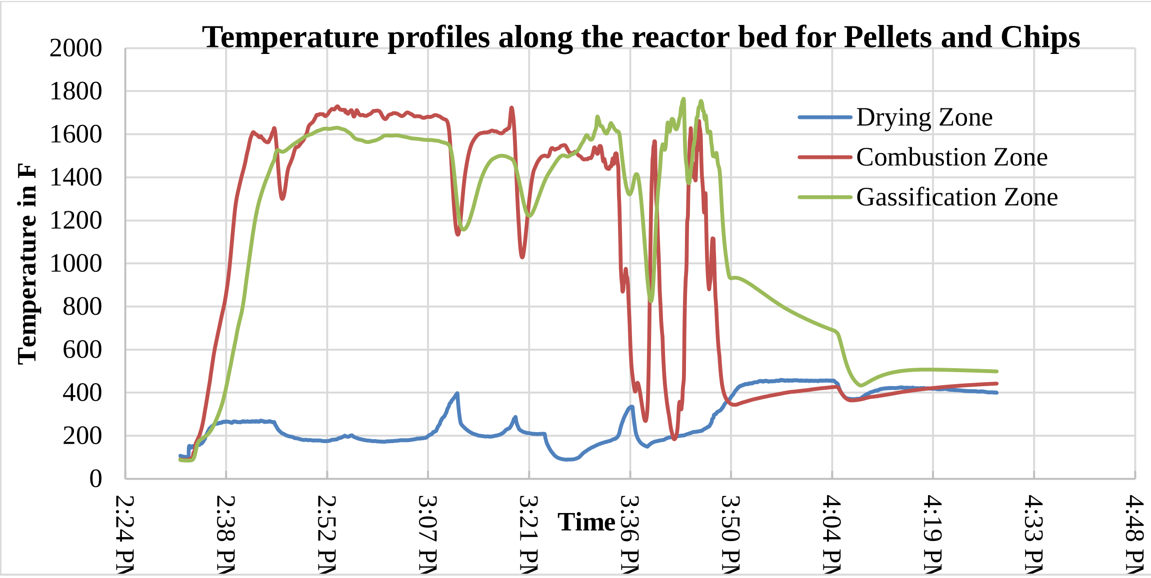
As discussed in Section 4, the process operation for 4” and 8” reactor for pellets, we observed that the feed rate, air flow to the reactor, syngas flame inside the combustion flare varies with the size of the reactor. As radius doubles, we observed that the feed rate and syngas flame in flare is approximately three times. Also, the important point to be considered is, the change in temperature profiles and maintaining a stable combustion and gasification bed inside the reactor is in control for the smaller size of reactors. So it is better to have smaller reactors connected in series for the same production of gas instead of using a bigger reactor which has a larger bed, but the costs for having many small reactors is much more than for one single bigger reactor. Here the difference between 4” and 8” reactors in terms of process operation is not much but when much higher diameter reactors are built then in that case, multiple smaller reactors are better and are easy to control.

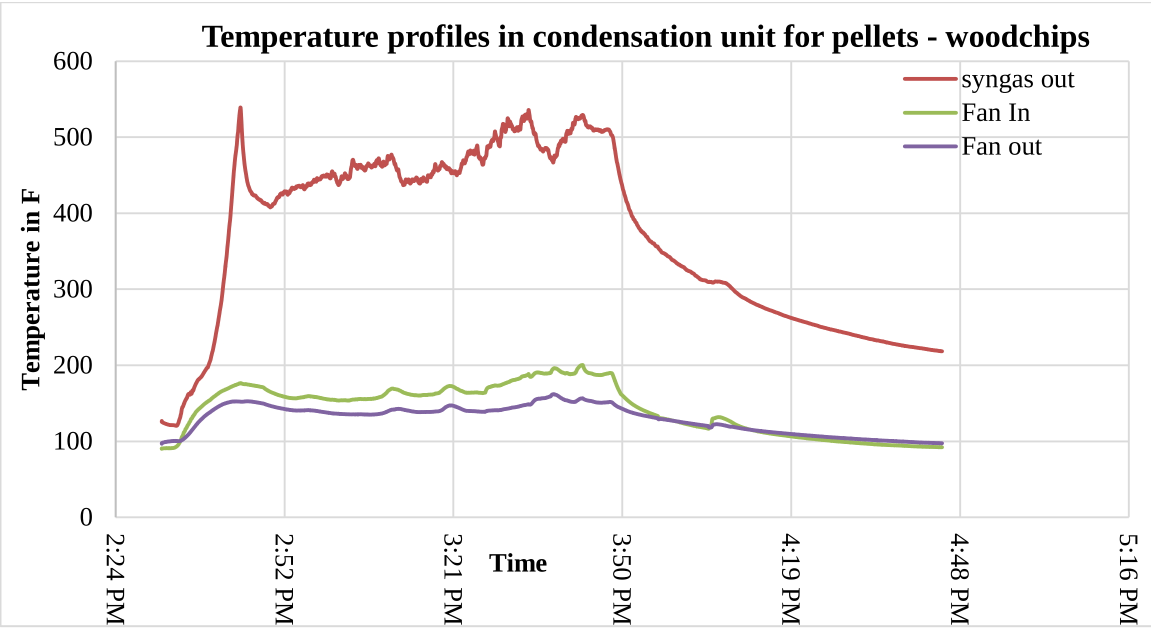
According to Section 5, for the biomass gasification of different feedstocks we studied how various factors such as shape and moisture content affect the operating procedure for the process. The Six Sigma methodology has helped us in analyzing and understanding how operational procedure changes based on the temperature profiles inside the reactor. Based on the statistical analysis, the detail variation in each process and how each feed varies the temperature profile of each zone is understood in the process along with reducing variation. The important points that are learned are the type of feed, feed rate to the reactor, valve setting or air flow to the system and vibration of the system plays a very important role in maintaining a steady state gasification process. Apart from this the numerical model in Section 6 is one important model for understanding the process inside the system in depth. This is an important tool to reduce the costs involved as this doesn’t involve actual building of the reactor. The proper particle flow or granular flow studied gives us the particles interaction along with the interaction between the walls.

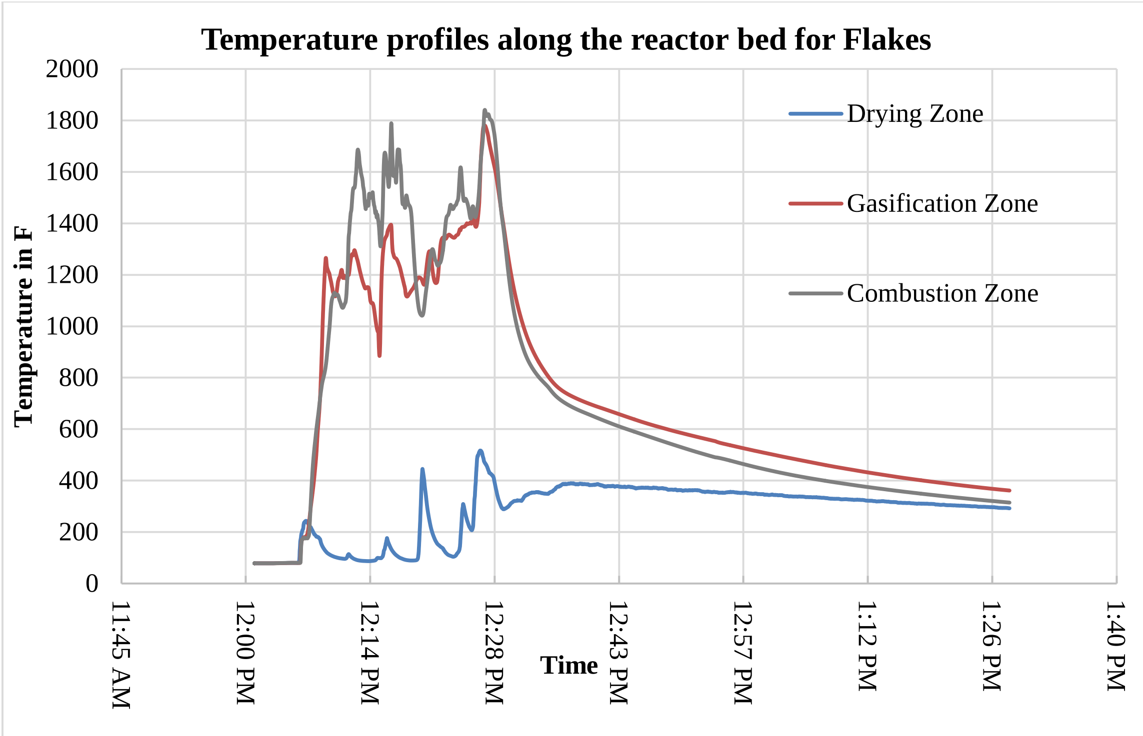
As a future work, it is recommended to work study the gasification process for 12” reactor and obtain a definite relation of how the size of reactor varies with its process operation. It is suggested to study the bio-oil and syngas compositions for different sizes of reactors and types of feed obtained at different temperature conditions. Also, it is suggested to measure the air flow and compare it to the temperatures inside the reactor with variation in flow. Furthermore, it is recommended to chop, dry and pelletize the flakes and picks before sending those in and compared the stability of the bed and flame inside the burner to the pellets again. A design of experiments may be conducted based on the air flow, quality, and quantity of syngas and bio-oil produced. The computational fluid dynamic model is to be worked for its reaction modelling and the proper boundary conditions. This study coupled with modelling and experimental runs with different set of feed and different sizes of reactors gives us an easy understanding of the biomass gasification process involving different biomass granular woody feedstocks.

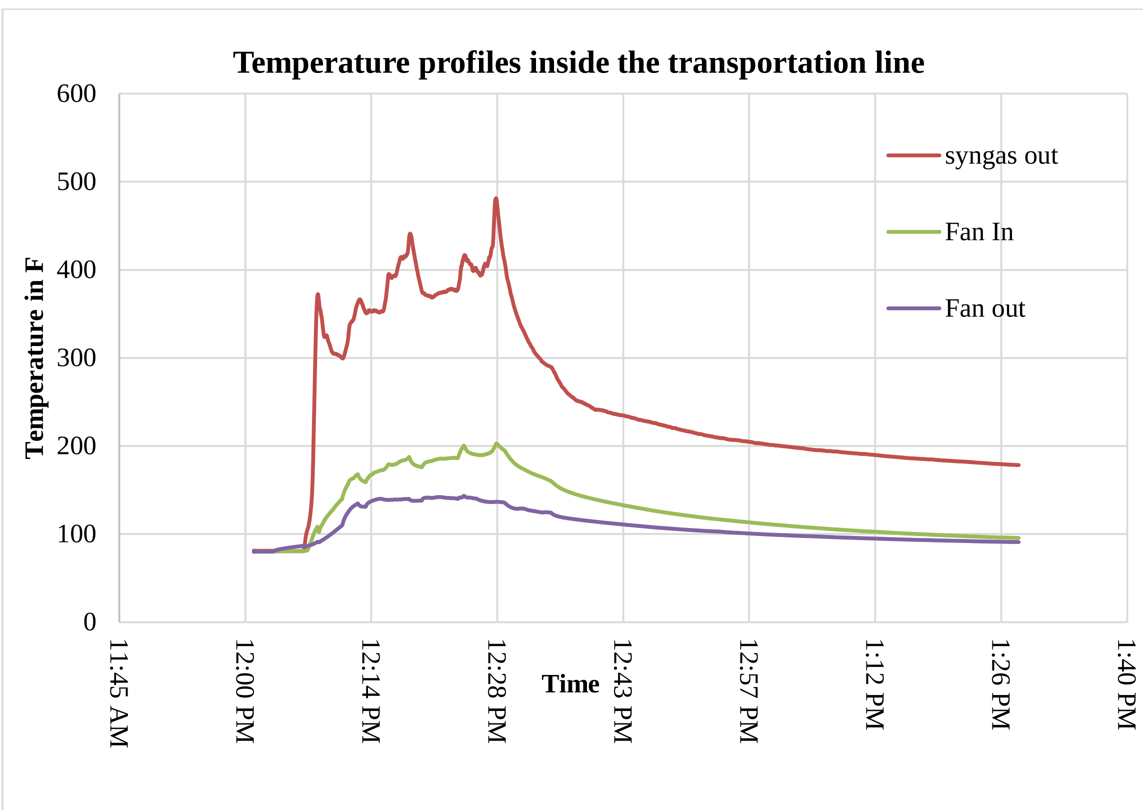
APPENDIX

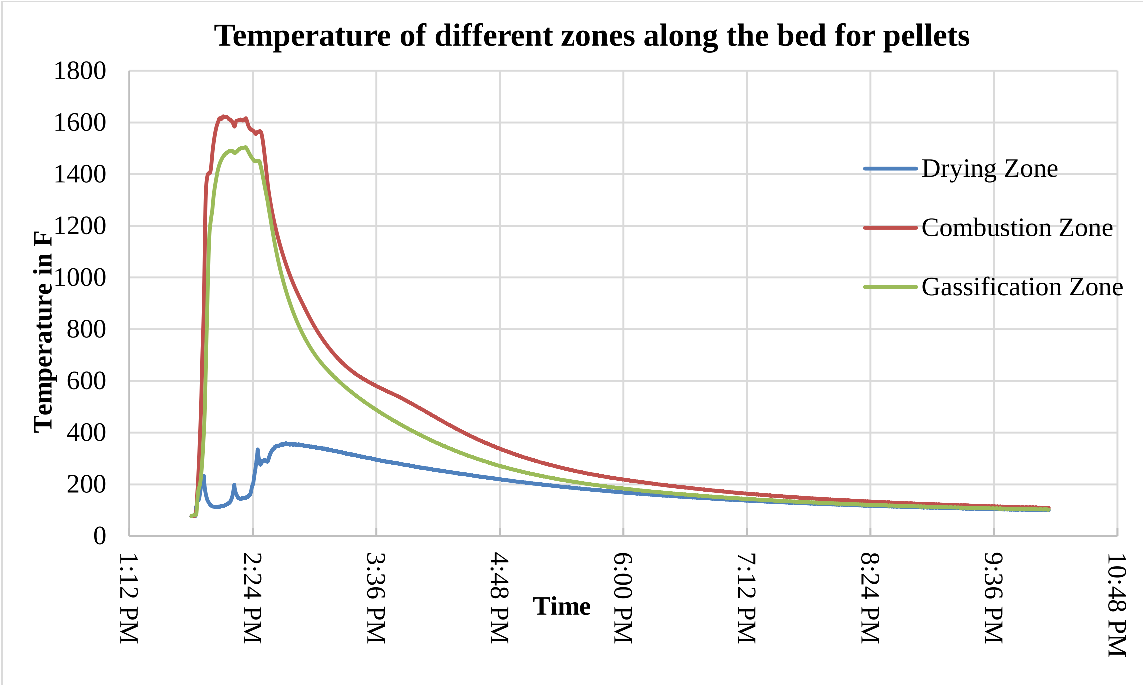
The graphs below are the temperature profiles of different zones for biomass gasification process with different feed stocks.

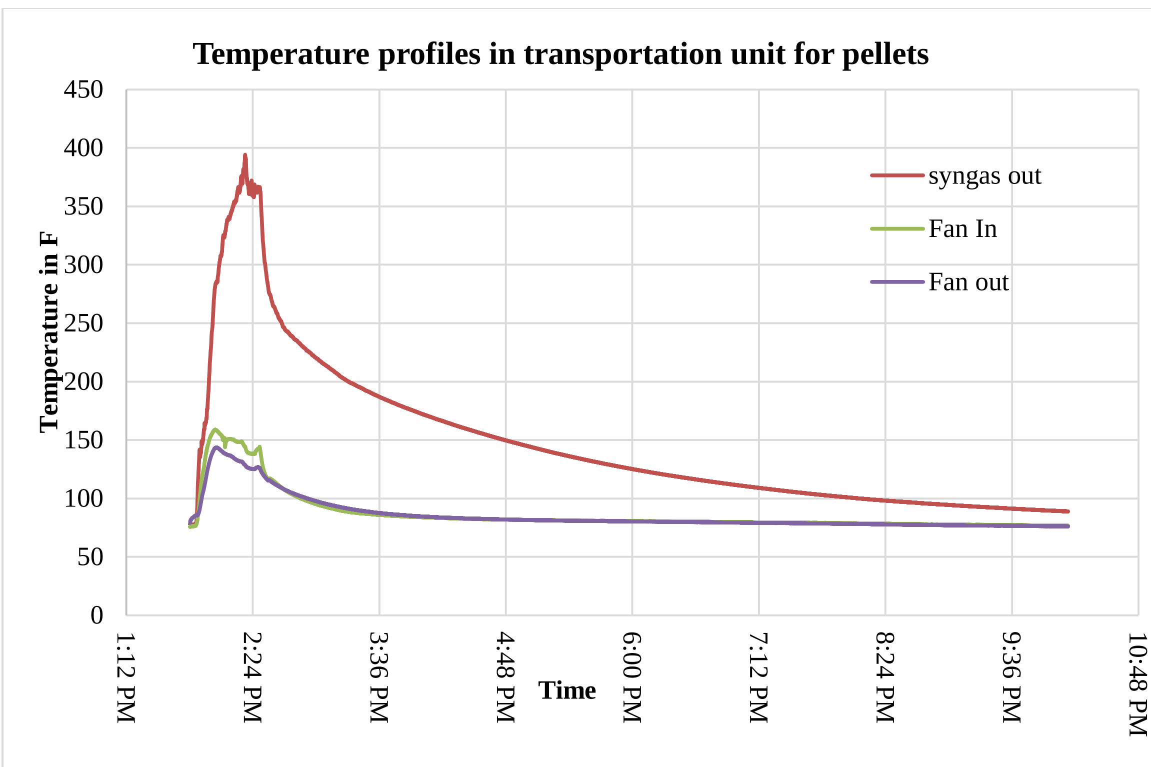





Temperature profiles along the reactor bed for Flakes
Temperature in F
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Drying Zone
Gasification Zone
Combustion Zone
11:45 AM
12:00 PM
12:14 PM
12:28 PM
12:43 PM
12:57 PM
1:12 PM
1:26 PM
1:40 PM
Time


Temperature profiles inside the transportation line
Temperature in F
600
500
400
300
200
100
0
syngas out
Fan In
Fan out
11:45 AM
12:00 PM
12:14 PM
12:28 PM
12:43 PM
12:57 PM
1:12 PM
1:26 PM
1:40 PM
Time


Temperature of different zones along the bed for pellets
Temperature in F
1800
1600
1400
1200
1000
800
600
400
200
0
Drying Zone
Combustion Zone
Gassification Zone
1:12 PM
2:24 PM
3:36 PM
4:48 PM
6:00 PM
7:12 PM
8:24 PM
9:36 PM
10:48 PM
Time


Temperature profiles in transportation unit for pellets
Temperature in F
450
400
350
300
250
200
150
100
50
0
syngas out
Fan In
Fan out
1:12 PM
2:24 PM
3:36 PM
4:48 PM
6:00 PM
7:12 PM
8:24 PM
9:36 PM
10:48 PM
Time

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VITA

Sai Chandra Teja Boravelli was born on in Kurnool Dist. of Andhra Pradesh state, India. Teja received her bachelor's degree in Chemical Engineering from Manipal Institute of Technology, Manipal, which is one of the renowned colleges in India. In her junior year, she found an internship opportunity to work with Dr. Reddy Laboratories which is the global organization in the pharmaceutical industry. During her senior year, she found an opportunity to work under prof. Laxman Kumar where she learned process modeling and simulation of heat exchangers using HTRI. She finished her undergraduate in May 2014 after which she applied to higher studies in the United States for her master's degree.

Teja joined as a graduate student in Chemical Engineering at Missouri University of Science and Technology in August of 2014 for a master's degree. There, she was given an opportunity to work as a graduate research assistant under Dr. Joseph Smith in Energy Research and Development Center of the university. Teja graduated with her master's degree in Chemical Engineering in December 2016 from Missouri University of Science and Technology.