Torrefaction Reactors

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Abstract

This paper reviews the torrefaction reactor technology, which is used for improving raw biomass properties. The operating principle of torrefaction reactor and classification of reactors i.e. laboratory, pilot, and commercial scale will be described in this paper.

Keywords: Fixed bed reactor, Fluidized bed reactor, Microwave reactor, Moving bed reactor, Torbed reactor, Torrefaction reactor.

Introduction

Nowadays biomass shows considerable promise for an alternative energy source. However, using raw biomass destined for combustion is challenged by several disadvantages and one of the drawbacks of biomass combustion is that it causes combustion instability resulted from high moisture content and large combustion chamber due to low energy density of this raw biomass. In order to improve the fuel properties of raw biomass, the torrefaction technology was conducted.[1 – 4] The first laboratory investigation of torrefaction process was began in France in the 1930s. At that time, the effect of temperature, heating rate and residence time on the process were investigated. In 1980s, Bourgois and Doat conducted their experiment testing on two types of wood and torrefaction temperature was varied at two values. Their work contributed to the pilot torrefaction plant in 1987s.[5] The torrefied biomass has been proven to have high energy density, hydrophobic characteristic, and durability of biodegradation.[6, 7] Torrefaction process in improving raw biomass properties, thus, has been gaining more attention in many parts of the world especially in Europe and North America.[8] This paper reviews the operating principle of torrefaction process and type of reactor in laboratory, pilot and commercial scale.

Operating principle of torrefaction process

Torrefaction process is a thermal degradation of raw biomass. The temperature for torrefaction process occurs in the range of 200 – 300^{0}C. The sub-procedure for torrefaction process can be divided into 4 procedures: 1) heating, 2) drying, 3) intermediate heating, torrefaction, and cooling, as can be seen in Figure 1. First, the raw biomass is heated up in heating procedure in order to increase the raw biomass temperature before going in to drying procedure. The temperatures of heating rate less than 50^{0}C per minute is recommended in heating procedure. When the raw biomass reaches the required temperature, generally around 90 - 105^{0}C, drying of raw biomass start. The free water inside biomass is evaporated and the moisture content of raw biomass is decreased. It is necessary that removal water from raw biomass is performed since the higher of water or steam in reactor result in obstruction of raw biomass thermal degradation in torrefaction procedure.[1] Once the drying process is completed, raw biomass was heated up to torrefaction temperature. The so-called intermediate heating, is required. In torrefaction procedure, the temperature of raw biomass is kept constant in the temperature range of 200 – 300^{0}C depending on type of raw biomass. During thermal degradation period, hemicelluloses in raw bio-

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mass generally decompose firstly at the temperatures range of 200 – 250^{0}C and later do lignin and partial of cellulose at 270 – 300^{0}C.[1, 2, 10] The change in composition of raw biomass from thermal degradation is shown in Figure 2. When torrefaction procedure is accomplished, the torrefied biomass increases in a high temperature and reacts with oxygen easily. Thus, the cooling of torrefied biomass is necessary in order to prevent hot torrefied biomass from spontaneous combustion.[1]

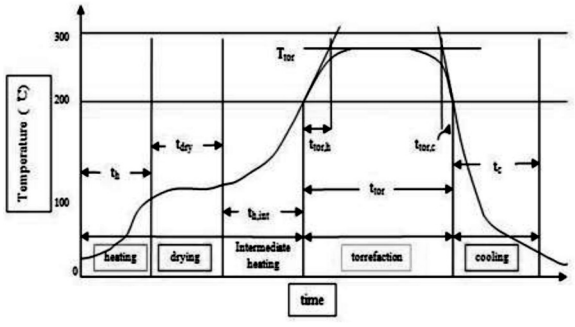

Figure 1 The sub-procedures of the torrefaction process[9] Classification and operating principle of torrefaction reactor

The torrefaction reactor can be classified into 3 scales i.e. laboratory, pilot, and commercial scale. The production capacity of laboratory scale reactor is less than 20 kg/hr, while the capacity of pilot and commercial scale is 20-600 kg/hr and more than 600 kg/hr, respectively.[1, 4, 10]

Laboratory scale torrefaction reactor

The laboratory scale torrefaction reactor was established for the first time in 1930s to investigate the parameters that affect torrefaction process.[5] The information from laboratory investigation was used for developing a pilot scale torrefaction reactor. Laboratory scale torrefaction reactor can be divided into 3 types as follows.

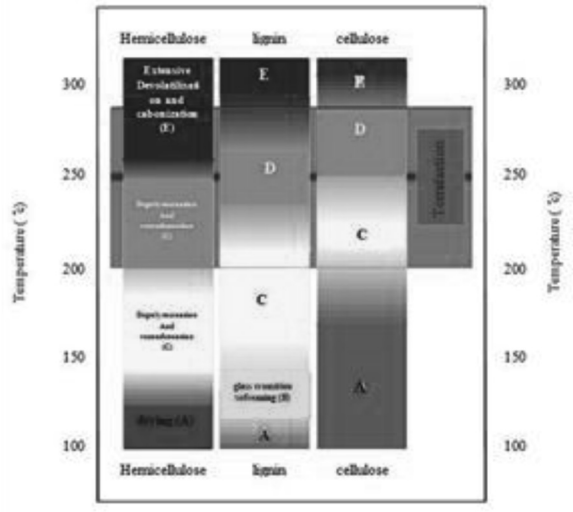

Figure 2 Change in composition of raw biomass from thermal degradation[11]

Fixed bed torrefaction reactor

The fixed bed torrefaction reactor is the simplest reactor. The fixed amount of raw biomass was filled inside the reactor, and was heated up by heat conduction from the electrical heater around the outside surface of reactor as shown in Figure 3. Jun et al.,[12] who studied the torrefied cotton stalk and wheat straw from fixed bed reactor, found that the biomass yields after torrefaction had higher energy density and improved grindability characteristics compared with raw biomass. In addition, torrefied biomass also showed hydrophobic characteristics.[12] Medic et al.[14] used corn stover as raw biomass in the experiment. It was found that the energy density of torrefied biomass increased by 2–19%, while the weight of torrefied biomass decreased by 45%.[14] Rousset et al.[15] studied the enhancing of the combustible properties of torrefied bamboo and compare its elemental characteristic with lignite and coal.[15] Uemura et al.[16] conducted investigation of oil palm waste.[16] Bridgeman et al.[17] investigated the grindability of torrefied energy crops: willow and miscanthus.[17]

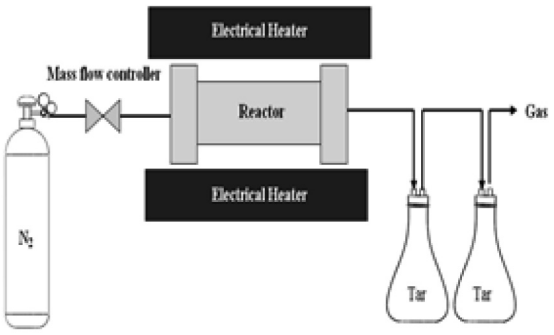

Figure 3 Fixed bed torrefaction reactor[13]

Microwave torrefaction reactor

Microwave torrefaction reactor uses the high frequency electromagnetic waves, so called microwave, for vibrating the water molecules inside biomass resulting in increase of biomass temperature. Wang et al.[18] constructed and tested microwave reactor. They suggest that the power level for torrefaction of rice husk and sugarcane residues is between 250 and 300 Watts. They also found that the caloric value of rice husk increase by 26% and 57% of sugarcane residues.[18] The microwave-induced torrefaction reactor is shown in Figure 4.

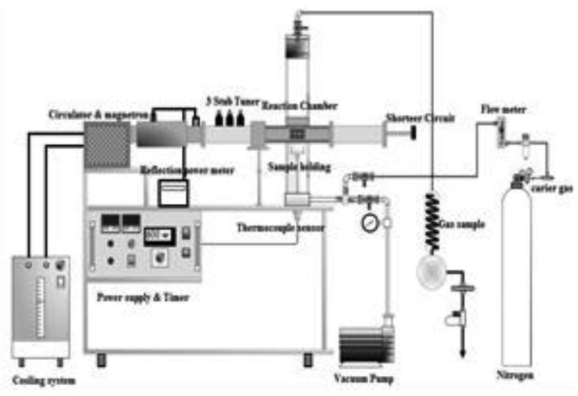

Figure 4 Microwave-induced torrefaction reactor[18]

Fluidized bed torrefaction reactor

The principles of the fluidized bed reactor are as follows. The raw biomass is placed on the grate, and the hot inert gas flows from the bottom through the raw biomass bed. At a suitable inert gas velocity, the raw biomass floats and behaves like a fluid. This results in uniformly thermal and temperature distribution throughout the raw biomass bed. The torrefaction of raw biomass bed occur through. The fluidized bed torrefaction reactor is shown in Figure 5. Li et al.[19] studied the torrefaction of sawdust in a fluidized bed reactor with nitrogen as inert gas. The nitrogen velocity was at 0.26, 0.29, and 0.32 m/s, respectively. The temperature of nitrogen was measured at 240, 250, 260, 270, 280, 290, and 300 ^{o}C. The residence time was 15, 20, 30, and 60 minutes. The study showed that when the severity of torrefaction was increased heating value of torrefied sawdust increase, while the energy yield decreases.[19]

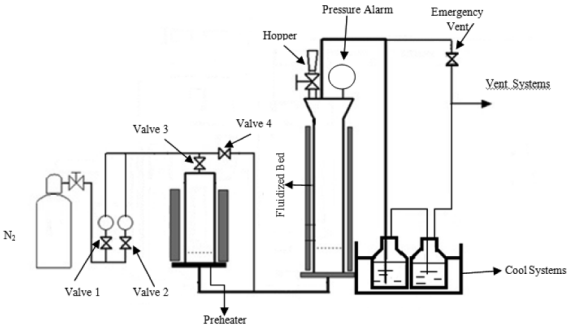

Figure 5 Fluidized bed torrefaction reactor[19]

Pilot scale torrefaction reactor

Based on the laboratory reactor results, pilot scale torrefaction reactor was developed. The data and parameter relation gathered from laboratory reactor will be verified by pilot scale torrefaction reactor. The pilot scale torrefaction reactor can be divided into 3 types as follows.

Fixed bed torrefaction reactor

The operation principle of fixed bed torrefaction reactor in pilot scale is similar to laboratory scale except the heat source. The pilot scale derives a heat from raw biomass combustion as heat source, while laboratory scale does from an electrical heater. The process diagram of pilot scale reactor is shown in Figure 6. Like a laboratory scale, a pilot scale reactor cannot be operated continuously. Energy research Centre of the Netherlands (ECN) designed and constructed this reactor in 2005s. The model is ECN bath reactor which has a production capacity of 20 l.[20] The ECN bath reactor model is shown in Figure 7.

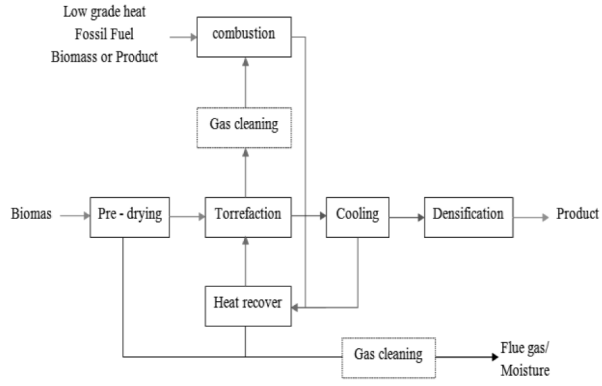

Figure 6 Process diagram of pilot scale reactor[20]

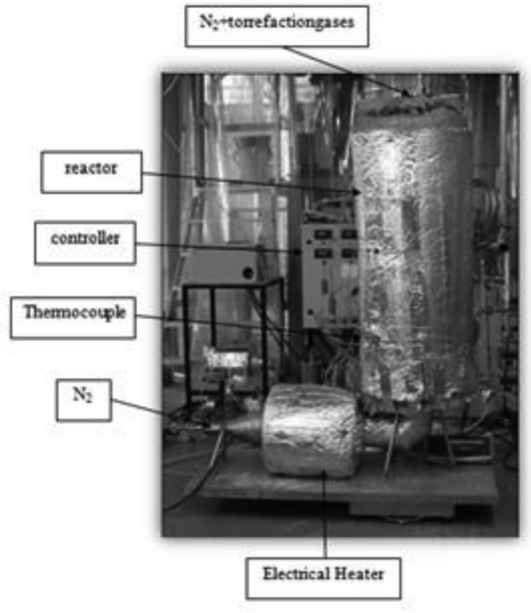

Figure 7 ECN bath reactor[20]

Fluidized bed torrefaction reactor

The pilot scale of fluidized bed torrefaction reactor was developed by Topell Energy in 2010s. The capacity of this reactor was 60,000 tons/year. This reactor has a short reaction time and higher heat transfer efficiency. Although this technology is readily to scale up, there are a problem about particle size limitation and attrition inside reactor.[21]

Moving bed torrefaction reactor

Moving bed torrefaction reactor uses mechanical mechanisms for moving raw biomass from entrance to exit of reactor. It can be divided into 3 types as follows.

Rotary kiln torrefaction reactor

The concept of rotary kiln torrefaction reactor is similar to commercial pyrolysis reactor. The raw biomass was fed by screw feeder in stationary reactor, while the heating element in rotary drum rotates around the reactor. The production capacity of pilot scale was 50 kg/hr. The preferable moisture content of raw biomass for this reactor was 10%-15%/wt. There are two methods for heating up rotary kiln reactor: direct heating and indirect heating. For direct heating, superheat steam was used as heating media, while the hot oil was used as heating media for indirect heating. The residence time of raw biomass depend on rotating speed of rotary kiln. The low rotating speed results in long residence time which consequently led to carbonization rather than torrefaction. This reactor has a limitation in scaling up because rotary kiln cannot be use with vary size of raw biomass. There are only one values of the raw biomass size that correspond to reactor length, which contributing the high quality of torrefaction biomass.[21, 22] The rotary kiln torrefaction reactor was shown in Figure 8.

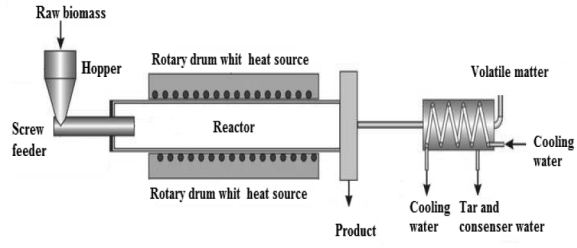

Figure 8 Rotary kiln torrefaction reactor[23]

Screw conveyor torrefaction reactor

The screw conveyor torrefaction reactor was shown in Figure 9.The raw biomass was conveyed through reactor by screw. The heat source for reactor is achieved by the flue gas from combustion. The raw biomass size for this reactor should smaller than 10 mm. In addition, raw biomass with very low bulk density and high moisture content is not suitable for this reactor. Because of the quality of torrefied biomass depend on the screw diameter, thus, it is difficult to scale up this reactor.[22] Energy research Centre of the Netherlands (ECN) designed and constructed this reactor in 2008s. It had product capacity of 60-100 kg/hr with operating temperature of 220-280 ^{o}C.[24]

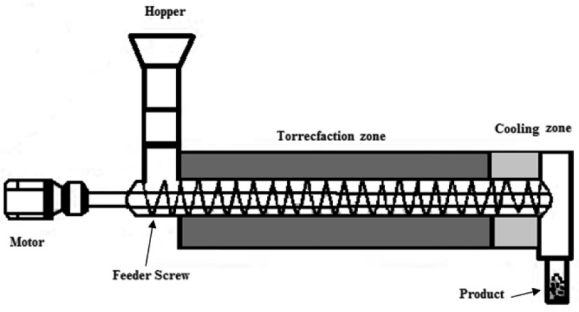

Figure 9 Screw conveyor torrefaction reactor[4]

Multiple hearth torrefaction reactor

The multiple hearth torrefaction reactor was shown in Figure 10. The biomass was fed from the upper side of reactor into the first hearth. The raw biomass was heated up by contact with hot surface of hearth. Later, the raw biomass was swept into the second hearth and next hearth by rabble teeth which installed on rabble arm.[22]

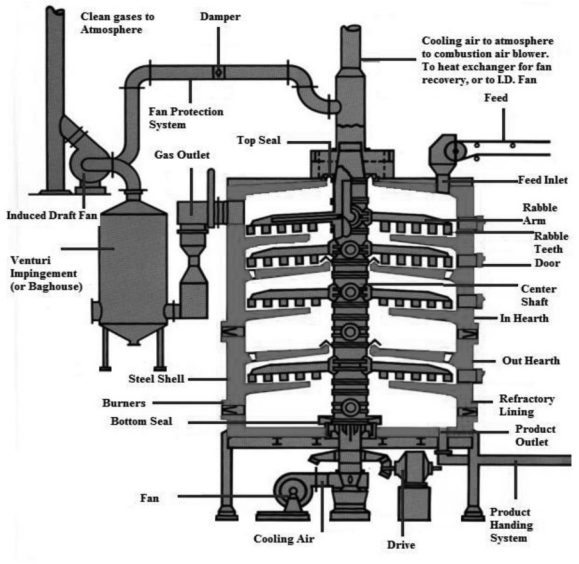

Figure 10 Multiple hearth torrefaction reactor[25]

The commercial scale torrefaction reactor

The commercial scale torrefaction reactor can be classified into 6 types as follows.

The fixed-bed torrefaction reactor

This reactor was developed for a long time because of its simplicity. The operating principle of this reactor is similar to pilot scale reactor. However there is a disadvantage for this reactor i.e. irregularly in temperature distribution throughout the reactor. Integrofuels company was established this reactor in the 2010s. The production capacity of reactor was 48,000 tons/year. It was found that the loss weight of biomass was 20-30% compare with initial weight, while retaining 90% of its energy.[26]

Torbed torrefaction reactor

Figure 11 show the torbed torrefaction reactor. By injection of high velocity gas about 50-80 m/s through stationary angled blade, toroidal flow pattern occurred. The gas particle lifts and move biomass bed horizontally at the same time results in shallow biomass bed moving around vertical axis at center of reactor. The heat and mass transfer occur in this bed easily which consequently led to short residence time and homogenous torrefied product.[22, 27] Topell tested torbed torrefaction reactor at Poland in 2007s. In 2010s, they designed and constructed this reactor with production capacity of 60,000 tons/year, and operating temperature of 280-320^{0}C. The residence time of this process was 90 seconds.1, 4

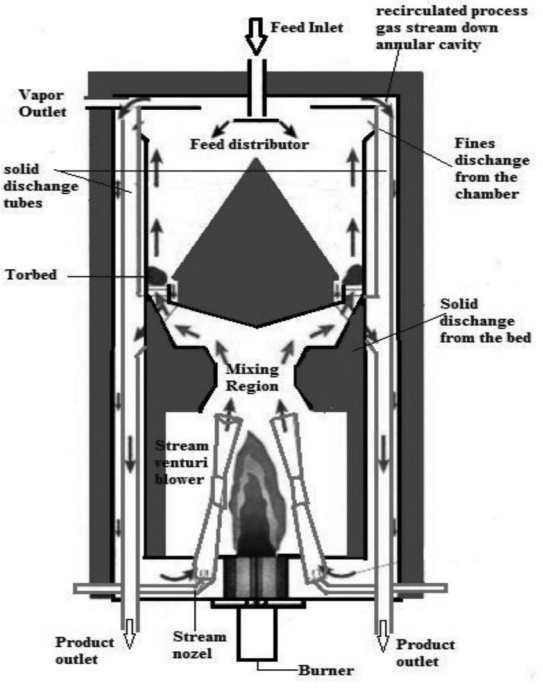

Figure 11 Torbed torrefaction reactor[27]

Oscillating belt conveyor reactor

The oscillating belt conveyor reactor is shown in Figure 12.The raw biomass is fed on belt conveyor into reaction. The belt conveyor is oscillated resulting in uniformly thermal distribution and torrefaction of raw

biomass on conveyor. Flue gas residue from torrefaction process was used for drying of raw biomass before being fed into reactor.[22, 27] This reactor was constructed in 2010s by Agritech Producer Columbia, namely Torre -Tech ® 5.0. Its operating temperature was in range of 300 - 400°C, reaction time was 30 min, and capacity was 50,000 tons/year. The product of this reactor retained 80% of raw biomass energy.[28]

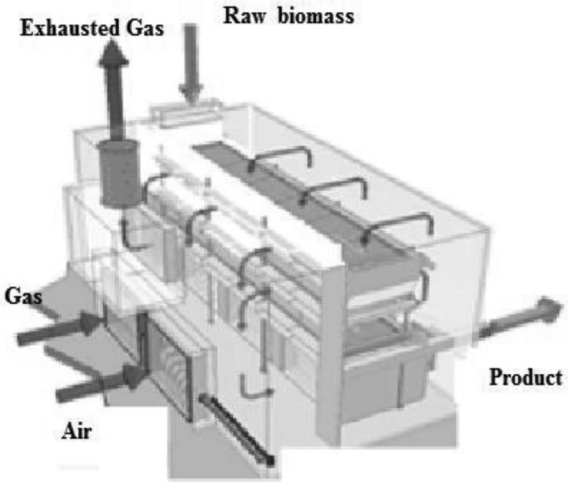

Figure 12 Oscillating belt conveyor reactor[26]

Rotary drum torrefaction reactor

The rotary drum torrefaction reactor was shown in Figure 13. The raw biomass passes through the reactor by lifting flights inside inner shell of rotary drum. The heating gas flows in gap between inner and outer shell. It is noted that inner and outer shells rotate together when this reactor was operated.[21] This reactor was established in 2011s by Bio Energy Development North AB (SWE). Its capacity was 25,000 - 30,000 tons/year and Atmosclear in 2010s with capacity of 50,000 ton/years.[4]

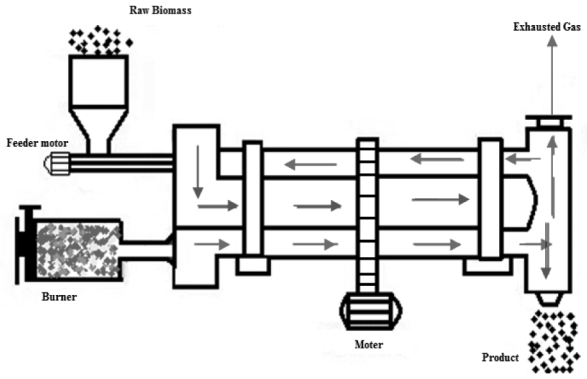

Figure 13 Rotary drum torrefaction reactor[4]

The microwave torrefaction reactor

The commercial scale of microwave torrefaction reactor was developed by Rotawave Ltd. in 2011s with production capacity of 110,000 tons/year.[4] The plant layout of this reactor was shown in Figure 14.

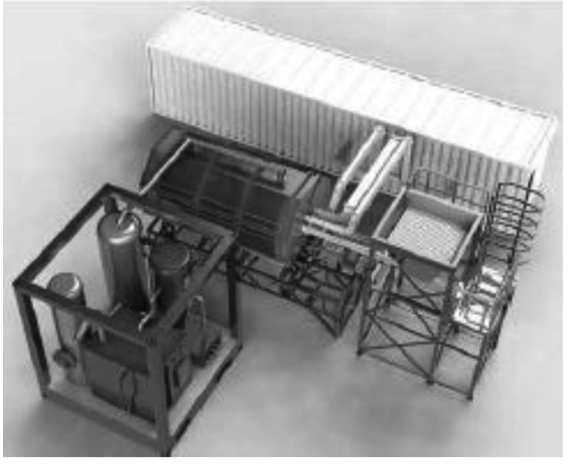

Figure 14 Plant layout of microwave torrefaction reactor[4]

The screw torrefaction reactor

The commercial scale of screw torrefaction reactor is developed by BioLake B.V. in 2010s with production capacity of 5,000-10,000 tons/year, and FoxCoal B. V. in 2012s with production capacity of 35,000 tons/year.[4] The plant layout of this reactor was shown in Figure 15.

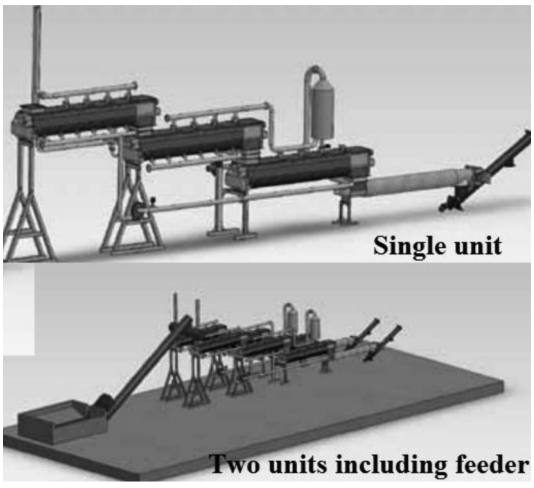

Figure 15 Plant layout of screw torrefaction reactor[29]

Conclusion

Torrefaction is technology for improving biomass properties. The torrefaction reactor can be divided into three scales: laboratory scale (including fixed- bed reactor, fluidized bed reactor and microwave reactor), pilot scale (including fixed- bed reactor, fluidized bed reactor and moving bed reactor), and commercial scale (including fixed - bed reactor, torbed reactor, oscillating belt conveyor, rotary drum reactor, microwave reactor and screw reactor). The operation principle and production capacity of each reactor were described in this reviews. Although there are many types of reactor, the further research in reactor design for minimum energy used is still need.

Acknowledgement

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