

Operating and Performance Gasification Process Parameters

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Abstract: *This paper aims to put together important key operational and performance parameters of a gasification process indicating their definitions along with their individual influence on the gasification conditions and/or products. Parameters considered are: equivalence ratio, superficial velocity, steam to biomass ratio, gasification temperature, composition and physical properties of biomass, inlet temperature and composition of the oxidant and tar content, It was found that a gasification process is dependent on each parameter by somehow. In fact, optimization of these parameters are of great importance on gasification product(s).*

Keywords: Gasification; parameter and superficial velocity

1. Introduction

Reviewing several available literature concerned with several gasification processes, it is clearly noted that use of several technical terms belong to the gasification process without introducing definitions for such terms. This can not be considered as a lack of information and weak scientific content of the reviewed papers since they fulfilled their allocated aims, it; however, has motivated the author of this paper, based on the available literature, to briefly state a definition for each term to avoid uncertainty. Generally and regardless of the gasification process or gasifier type, these terms to a large extent evidently seem crucial to a gasification process. Abounding and variety of such parameters may indicate the extent of complication of gasification process through their synergic action. In fact, one should be careful how to manipulate these parameters to ensure optimum gasification efficiencies of a given biomass. Some of these terms are operational while others are to do with gasification process performance. The following sections collectively constitute the aim of this paper that is to describing some of these parameters along with their individual influence on the gasification conditions and/or products.

2. Operating and Performance Gasification Process Parameters

2.1 Equivalence Ratio (ER)

One measure of air/oxygen flow rate in a gasification process is ER. It represents the ratio between the amount of air/oxygen carried in the gasification agent (oxidant) and theoretical amount of air/oxygen required for complete combustion of the feedstock (biomass) according to stoichiometry (Gabra, et al., 2001; Venkata, et al., 2008; Sheth P. N. and Babu B. V., 2010; Zhao, et al., 2010; Kezhen, et al., 2013; Sharmina, et al., 2013; Wu, H., 2013; Xu, Q., 2013). ER is a measure of the extent of partial combustion (Yamazaki, et al., 2005). Operationally, ER is an important parameter as according to it composition of the synthetic (syn) gas produced and chemical energy may vary. With a higher ER value more carbon dioxide in the syn gas can be produced with less carbon monoxide (CO).

Reduction in the amount of carbon monoxide associated with a higher ER value can be explained that with a higher ER value more oxygen is introduced and there should have been more carbon monoxide converted, through oxidation, to carbon dioxide (CO₂) (Turn, et al., 1998; Thanasit, et al., 2013; Wu, H. 2013). With a lower ER value less hydrogen (H₂) and methane (CH₄) are produced (Park, et al., 2014). Low ER values approaching zero are usually encountered in pyrolysis step where as high ER values approaching/greater than one are usually encountered in combustion step next to pyrolysis. Low ER values can be associated with high tar as well as production of unconverted char. High ER values are to do with syn gas oxidation and heating value. Although with a high ER value, combustion may not be complete and heating value of syn gas may be reduced (Devi et al., 2003; Li et al., 2009; Arena et al., 2010; Asadullah, M., 2014), high ER values are commercially desired due to maximum char conversion possibility. ER is a function of air/oxygen flow rate as well as biomass feeding rate (Kezhen, et al., 2013).

ER= Actual air/oxygen in the oxidant/stoichiometric air/oxygen (Alok D. and Gupta .V.K., 2014).

In case the amount of air/oxygen carried in the gasification agent (oxidant) is less than the theoretical amount of air/oxygen required for complete combustion of the feedstock (biomass) according to stoichiometry, value of ER becomes less than 1; this is known as fuel-lean conditions. Nevertheless, in case the theoretical amount of air/oxygen required for complete combustion of the feedstock (biomass) according to stoichiometry is less than the amount of air/oxygen carried in the gasification agent, value of ER becomes more than 1; this is known as fuel-rich conditions. Both fuel-lean/rich conditions can be used to study the conversion rate of NH₃ present in a syn gas into NO_x. In such a study, effect of the molar ratio of CO/H₂ is vital and may show different tendencies. Further details on this can be found elsewhere (Fenimore, C.P., 1972; Sarofim, et al., 1975; Kato, et al., 1976; Takagi, et al., 1977; Hasegawa, T.; Sato, M., 1997; Hasegawa, et al., 2001; Hasegawa, T., 2009).

In addition to gasification process, ER is also used in pyrolysis and combustion processes. Ranges of values of ER in each process are; nevertheless, distinct (Xu, Q., 2013).

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As pyrolysis is carried out in the absence of oxygen, its ER value is zero ($ER=0$). In combustion, values of ER approach or exceed one ($ER\geq 1$) in an effort to provide sufficient air/oxygen by which complete oxidation reactions can take place. However, for partial oxidation reactions, i.e., gasification, ER is usually between 0.25 and 0.5 (Xu, Q., 2013) and never approaches one.

2.2 Superficial Velocity (SV)

In addition to ER, SV is also a measure of air/oxygen flow rate. SV is, once more, a ratio that relates air/oxygen flow rate to the cross sectional area of the gasifier (Yamazaki, et al., 2005).

Air/oxygen flow rate is a vital factor for the products of a gasification process due to its multiple rather synergistic effects. One obvious effect of oxygen (oxidant) flow rate, whether it is fed to the gasifier as a pure oxygen or is contained with air, is on the degree of combustion of fuel (biomass). A higher degree of combustion can be obtained at a higher oxygen flow rate. This can be directly correlated to an increase in the temperature inside the gasifier due to the exothermic nature of combustion reactions. This has the effect of boosting the conversion of biomass and promoting the quality of syn gas. On the other hand, excessive degree of combustion should be avoided. With an excessive degree of combustion, part of energy content of the syn gas generated may be lost following consuming a part of biomass during combustion losing some of its energy content. Also, in case of a fluidized bed gasifier has been used, increased oxygen flow rate may promote fuel fluidization. However, higher oxygen flow rate may shorten the residence time of the fuel (biomass) and generated gases inside the gasifier which may have the consequence of reducing the conversion of biomass (Narváez, et al., 1996; Lv, et al., 2004; Wang, et al., 2007; Kumar, et al., 2008; Ajay, et al., 2009).

2.3 Steam to Biomass Ratio (SBR)

In steam gasification where steam is used as a gasification agent, SBR is an important parameter. SBR is the mass ratio of steam to biomass (Wu, H., 2013). At a constant temperature, higher SBRs give more H_2 while lower CO and CH_4 . Such an increased amount of H_2 can be explained by the fact that upon supplying steam to the gasifier, provided that the gasifier is maintained at a reasonably high temperature higher than 750-800 °C (Lucas, et al., 2004; Gupta, A.K. and Cichonski, W., 2007; Kumar, et al., 2009), it can increase the partial pressure of H_2O inside the gasifier by which water-gas reaction, water-gas shift reaction and methane-reforming reaction are favoured by which production of H_2 is increased. On the other hand; a decreased amount of CO and CH_4 as a result of increased SBR but at a constant temperature can be due to steam-reforming reaction (Wu, H., 2013). It should be pointed out that although for the above reactions to proceed a catalyst(s) may be required, presence of a catalyst(s) may lower the gasification temperature required for such reactions to take place (Maschio, et al., 1994; Ajay, et al., 2009). However, at a certain SBR but increased temperature, H_2 production decreases while production of CO increases as a result of the

exothermic and reversible behavior of water-gas shift reaction which becomes unfavorable as gasification temperature increases. Also according to Le Chatelier's principle, increasing temperature and also increasing SBR results in the production of more H_2 . Moreover, decreasing temperature while increasing SBR results in more hydrogen than CO that's a higher value of H_2/CO ratio as a result of faster water-gas shift reaction (Abrar, et al., 2010). Similar results were also reported by (Sharmina, et al., 2014). With respect to tar, increasing SBR can decrease tar as a result of steam reforming of tar as the partial pressure of steam increases (Ajay, et al., 2009).

2.4 Gasification Temperature

In a gasification system, there is no one constant temperature at which the system is operated as every step, through out gasification, may hold a different temperature. Generally, three classes can be identified: low, medium and high in which temperatures range between: (400-600 °C), (600-900 °C) and (900 °C and higher), respectively (Thanasit, et al., 2013). Instead of temperature, temperature profile through different steps is the correct term that should be used. Whether the system is auto or allo-thermal operated, temperature profile is an important operational parameter. In an auto-thermal gasification system, temperature profile varies according to: composition, inlet temperature and chemical energy content of the solid biomass (fuel), degree of gasifier insulation, residence time and ER. In an allo-thermal system, required temperature is controlled in reference to the heat supply. A temperature profile can give an idea about the state of ash and tar formed following a gasification process (Devi et al., 2003; Arena et al., 2010). In steam gasification where steam reforming reactions are endothermic and *do* require higher temperature(s), gasification process needs to be run at elevated temperatures (Moghtaderi, B., 2007). Increasing gasification temperature can be advantageous meanwhile disadvantageous with regards to syn gas composition, tar concentration and ash build up. With boosting gasification temperature, more H_2 , that can be used as a clean energy carrier for heat supply and transportation purposes (Wei, et al., 2007; Li, et al., 2009), can be produced with carbon conversion efficiency and syn gas heating value and yield are also increased (Narváez, et al., 1996; Gupta, A.K. and Cichonski, W., 2007; Lv, et al., 2007; Gonzalez, et al., 2008; Ajay, et al., 2009; Kumar, et al., 2009; Thanasit, et al., 2013; Muhammad, et al., 2014; Sharmina, et al., 2014). Production of more H_2 can be attributed to the endothermic nature of steam-reforming reaction as well as to water-gas reaction by which H_2 is produced, although this may lead to lower CH_4 being produced (Ajay, et al., 2009). Such a drop in CH_4 production as a result of temperature increase can be due to a contribution of the reaction of steam reforming/ wet reforming reaction being shifted to the right as temperature is increased (Gonzalez, et al., 2008; Wu, H., 2013). Also, with further increase in gasification temperature, steam-reforming reaction or water-gas reaction and the Boudouard reaction become predominant by which more CO is produced. This result was also obtained by Shen and others (Shen et al., 2008). This can be linked to Chatelier's principle that higher temperatures favour the reactants in the exothermic reactions (Water shift reaction/ homogeneous

water-gas shift reaction) while favour the products in endothermic reactions (steam-reforming reaction or water-gas reaction and the Boudouard reaction) (Lv, et al., 2004; Kannang, et al., 2012). Disadvantages of increasing gasification temperature are: obviously increased energy input; thus, increased cost and high tar yield (Moghtaderi, B., 2007; Thanasit, et al., 2013).

Although measurement of gasification temperature is important, it can be a challenging task. As mentioned earlier, temperature throughout gasification *does* swiftly change making recording a certain constant temperature a nightmare (Higman and Burgt, 2003). Erosion by particulates, attack by molten slag of variable compositions and hot corrosive gases, including alkali vapour can also be other challenges of measuring the temperature during a gasification process (Heppner, J., 2008). In gasification systems, temperature can be measured by thermocouples or thermistors. Both thermocouples and thermistors are characterized with limited span life and also limited accuracy due to deviation from the actual temperature inside the gasifier. So far, there have not been: good thermocouples that can resist high temperatures inevitably encountered in the gasifier, good thermocouples that do not break easily nor good thermocouples that give stable and most importantly repeatable reading(s). Also, thermistors which are not as rugged as thermocouples, have package size and low sensitivity problems in a wide range of temperatures (Abdelaziz, et al., 2004).

2.5 Residence Time

It represents the required time for particles of the gasified waste (biomass) to completely convert into combustible gases remaining within the gasifier. It can be affected by gasification temperature, particle size and gasifier design (Lapuerta, et al., 2008; Hernandez, et al., 2010). With increased gasification temperature, residence time can be shorter. Also, with reduced particle size overall gasification process efficiency can be improved; thus, reducing the required residence time. A correlation between the residence time and particle size is given by (Rapagna, S. and di Celso, G. M., 2008) as shown in the following equation. The gasifier design may affect the residence time of particles of the gasified waste through flow configuration in relation to the gasifier type used. It is known that a particle transports under several forces such as gravity. Thus, using a down-draft gasifier in which the flow is downwards acting with the same direction of gravity may require a shorter time than that required when using a horizontal or up-draft gasifier for a given gasification process.

$$\tau = 2.673d^n$$

where: d is the particle diameter, mm
and $n = 1.02e^{233/T}$ where T is the particle temperature, K

2.6 Composition and Physical Properties of Biomass

In addition to the operational parameters of gasification on its own, composition and physical properties of biomass to be gasified can also enhance the performance of a gasifier. In terms of composition, biomass elemental composition as well as its composition of other pollutants such as: nitrogen, sulfur, alkali compounds and heavy metals. According to the

composition of a biomass, it is possible to feed more than one type of biomass to the gasifier as a mixture to utilize their synergic action to improving gasification process performance through reducing loss of carbon while increasing energy content of syn gas produced (Pinto, et al., 2007; Pinto, et al., 2008). Important physical properties of biomass that are of a great effect on gasification process are: its moisture content, bulk density, particle size, lower heating value, content of volatile matter and content of ash along with its composition (Zevehoven et al., 2001; C-Tech, 2003). In an effort to improve these properties of biomass through modifying them to improve efficiency of gasification process, biomass is usually pretreated prior to gasification. Details of pretreatment of biomass can be followed elsewhere (Rapagna, S. and Latif, A., 1997; Faaij, et al., 1998; Chin OC and Siddiqui KM, 2000; Koppejan, J. and Meulman, P.D.M., 2001; Lehtikangas, P., 2001; Cummer, K.R. and Brown, R.C., 2002; Dogru, et al., 2002; McKendry, P., 2002; Demirbas, A., 2004; Maker, T. M., 2004; Mani, et al., 2004; Morenol, et al., 2004; Bergman, et al., 2005; Mani, et al., 2006; Chen, et al., 2009; Kirubakaran, et al., 2009; Kumar, et al., 2009; Kers, et al., 2010; Wu, et al., 2011; Mupondwa, et al., 2012; Wang, W., 2013; Asadullah, M., 2014). In general, pretreatment is concerned with eliminating, as possible, heterogeneous characteristics of biomass through reducing its particle size in an effort to attain a uniform particle size distribution. It is also concerned with reducing the moisture content of a biomass through drying.

2.7 Inlet Temperature and Composition of the Gasification Agent (Oxidant)

Inlet temperature of the oxidant to the gasifier can be interrelated to temperature profile along the gasification process and, in line to an end-use appliance requirements, e.g. internal combustion engine, to recovery of heat from the produced syn gas (Arena et al., 2011). Usually, the inlet temperature of the oxidant to the gasifier would certainly be much lower than that of the gasifier since gasification processes employ quite high temperatures. Although it might require a significant amount of heat, as a remedy; however, a pre-heater should be installed prior to the gasifier to raise the temperature of the oxidant by which conversion efficiency (Basu, et al., 2009; Mathieu, P. and R. Dubuisson, 2002), hydrogen generation (Qiuhui, et al., 2014), heating value of syn gas produced and its quality (Qiuhui, et al., 2014) can be increased whilst reducing tars and char residues (Lucas, et al., 2004). Otherwise, there will be a point at which instead of the temperature of the gasifier bed is boosted, as gasification reactions *do* require, it is lowered (Barneto, et al., 2009). Composition of the oxidant synergically with its inlet temperature can influence mass and heat balances around the gasifier. Different oxidants or oxidants with different compositions may promote production of certain chemical species while inhibiting production of others within the produced syn gas. For instance, using steam as an oxidant produces hydrogen at higher yields than other agents but with no nitrogen. On the contrary, air gasification, will definitely lead to the production of nitrogen among its products. In either case, generated heat will of-course differ accordingly.

2.8 Cold Gas Efficiency (CGE)

Is the ratio between chemical energy of generated syn gas and chemical energy of the biomass fed to the gasification system. Chemical energy of generated syn gas represents the product of multiplication of net heating value of syn gas and its flow rate. While chemical energy of the biomass fed to the gasification system is represented by the product of multiplication of net heating value of biomass and its flow rate. A syn gas with a high CGE is desirable for power applications where as lower CGEs are preferred for syn gas synthesis-based applications (Higman and Burgt, 2003). Mathematical representation of CGE is as follows:

$$CGE (\%) = \frac{(LHV_{syn\ gas})(Q_{syn\ gas})}{(LHV_{biomass})(Q_{biomass})} * 100$$

Where: $LHV_{syn\ gas}$ is the lower heating value of the produced syn gas,

$Q_{syn\ gas}$ is the chemical energy of the produced syn gas,

$LHV_{biomass}$ is the lower heating value of biomass, and

$Q_{biomass}$ is the chemical energy of biomass.

CGE only considers the potential chemical energy contained in a biomass and syn gas generated; it does not consider the sensible heat of syn gas, that is why it is termed cold.

2.9 Hot Gas Efficiency (HGE)

Is the ratio between total chemical energy along with sensible heat of produced syn gas out of a gasification system and total chemical energy along with sensible heat of biomass fed to the gasification system. Mathematical representation of HGE is as follows:

$$HGE (\%) = \frac{[H_{out} + (Q_{syn\ gas})(LHV_{syn\ gas})]}{[H_{in} + (Q_{biomass})(LHV_{biomass})]} * 100$$

Where: H_{out} is the sensible heat of the produced syn gas,

$Q_{syn\ gas}$ is the chemical energy of the produced syn gas,

$LHV_{syn\ gas}$ is the lower heating value of the produced syn gas,

H_{in} is the sensible heat of biomass,

$Q_{biomass}$ is the chemical energy of biomass, and

$LHV_{biomass}$ is the lower heating value of biomass.

2.10 Carbon Conversion Efficiency (CCE)

It is again a ratio value and represents the ratio between flow rate of converted carbon into gases within the syn gas and flow rate of carbon originally fed to the gasifier with the biomass. Or equivalently, it represents the ratio of mass of the remaining (unconverted) carbon to the original carbon mass in the biomass. Thus, it can be used as an indication of the consumption of carbon (Xu, Q., 2013). CCE can give an idea about the reactivity of biomass material fed to a gasifier, a high CCE value corresponds to high carbon conversion and vice versa. A low CCE value, which means that little carbon under the effect of gasification has been converted to gases, is associated with high amount of unconverted carbon which requires some sort of treatment or disposal. Mathematical representation of CCE in terms of flow rate is as follows:

$$CCE = \frac{Q_{carbon\ in\ syn\ gas}}{Q_{carbon\ in\ biomass}}$$

$$Q_{carbon\ in\ syn\ gas} = (Q_{syn\ gas} * C_{fraction\ in\ syngas})$$

$$Q_{carbon\ in\ biomass} = (Q_{biomass} * C_{fraction\ in\ original\ biomass})$$

$$\text{Thus, } CCE = \frac{(Q_{syn\ gas} * C_{fraction\ in\ syngas})}{(Q_{biomass} * C_{fraction\ in\ original\ biomass})}$$

Where: $Q_{carbon\ in\ syn\ gas}$ is the flow rate of carbon converted to gaseous products,

$Q_{carbon\ in\ biomass}$ is the flow rate of carbon originally present in the biomass,

$Q_{syn\ gas}$ and $Q_{biomass}$ are the flow rate of syn gas generated and the flow rate of biomass feeding, respectively, and

$C_{fraction\ in\ syngas}$ and $C_{fraction\ in\ original\ biomass}$ are the fraction of carbon in the gaseous component of the syn gas and that originally present in the biomass, respectively,

Similarly, CCE in terms of mass of biomass is as follows (Abrar, et al., 2010):

$CCE (\%) = \frac{\text{gasified carbon in the product (g)}}{\text{original carbon in biomass feed (g)}} * 100$

2.11 Tar Content

Due to its complex content of poly-aromatic and condensable hydrocarbons such as ring aromatics and also oxygen-based hydrocarbons, tar is problematic to gasification process equipment and requires removal or treatment. If tar has not been removed, it may damage process equipment during gasification or damage the appliances that receive the produced syn gas, e.g. a turbine. Slagging, blockages and corrosion problems in boilers and other equipment are also issues can be caused by the presence of tar by which the overall gasification process performance is diminished. Tar can also damage catalyst(s) used for reforming reactions, ceramic filters used for particulates removal and sulfur scrubbers used for sulfur removal in a gasification system. Removal of tar can be carried out on a wet basis in which water is used. This; however, results in the transfer of this tar from the syn gas down to wastewater. This, in turn in the first instance, results in losing the chemical energy contained in the tar and leaving behind a wastewater (Milne et al., 1998, Devi et al., 2003, Arena et al., 2010).

2.12 Biomass Flow Rate

Feeding of a biomass to a gasifier may affect energy efficiency obtained from a given gasification process. Overall process conversion efficiency may be reduced if the biomass has been overfed to the gasifier by which plugging may be caused. Similarly, by starve-feeding syn gas yield may be diminished. To avoid this and that, optimum biomass flow rate should be in place. Such an optimum mainly depends on nature, main constituents and properties of biomass as well as gasifier design (Ajay, et al., 2009).

According to these parameters, quality of syn gas produced, out of a gasification process, can be assessed. Ranges of typical values of key parameters using oxygen or air as a gasification agent of municipal solid waste but not for biomass can be found elsewhere (Knoef, 2005; Grimshaw and Lago, 2010; Hankalin et al., 2011; Suzuki and Nagayama, 2011; Tanigaki et al., 2012). According to the best knowledge of the author of this paper, there has not been such a list for biomass gasification in the available literature.

3. Conclusions

Important operational and performance parameters of gasification process such as ER, SV, SBR, gasification temperature, composition and physical properties of biomass, inlet temperature and composition of the oxidant and tar content, etc., have been discussed in this paper. Optimization of these parameters are of great importance on gasification product(s). If the production of both H₂ and CH₄ is to be maximized, ER should be high enough, although this might be at the expense of the heating value of the syn gas produced due to incomplete combustion. Also, More H₂ can be obtained with a high SBR, provided that the temperature is kept constant. Moderately high flow rate of air/oxygen into the gasifier may enhance combustion reactions by which quality of syn gas can be enhanced. Too high air/oxygen flow rate may lead to wasting part of syn gas energy content. Temperature is a critical parameter in a given gasification process, it can be detrimental while beneficial, care should be paid. Also, temperature of the oxidant used should be high enough so as to gasification process conversion efficiency can be improved. Composition and physical properties of biomass to be gasified should be monitored properly prior to gasification. Among syn gas products, tar is the most notorious one. Accordingly, its removal from the syn gas is a crucial process.

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