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Gasification of potato shoots: An experimental and theoretical investigation

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ABSTRACT

A thermodynamic equilibrium model was developed to predict the gasification process in a bench-scale fluidized bed gasifier. Potato shoot (leaves and stems) was used as the feedstock of the gasifier. The experiments were done in five different gasification zone temperatures (650, 700, 750, 800 and 850°C), with a feeding rate of 0.166 kg/hour, and two equivalence ratios (ER: 0.2 and 0.25). The produced gas was analyzed and the portion of each component was calculated from a thermodynamic equilibrium model. The data from the experiments were compared with those of the modeling in order to validate the model. For 650°C, the closest results of the model to experiment data were observed for CO_2 at ER = 0.2, followed by CO at ER = 0.25 with errors of 7% and 21%, respectively. The least difference between the model data and the experimental data at 700°C was observed for N_2 with the error of 26% and 22% for ER= 0.2 and 0.25, respectively. At 750°C, the predicted values conformed reasonably well to the experimental data for CO with error less than 7%. Regarding the least error, the most admissible results were seen at 800°C for N_2 with ER= 0.25 with an error of 7%. In this case, the most acceptable results of the model were obtained for 850°C, in which the error in predicting the amount of CH_4 at ER= 0.25 was 0. Owing to the applicability of potato shoot in the gasification process, it can play a great role in energy production.

Keywords: Fluidized-Bed, Gasifier, Modeling, Potato Shoot, Thermodynamic Equilibrium Model.

1. Introduction

Renewable energy, in recent years, has become one of the most important concerns for most countries due to diminishing fossil fuels. Different methods have been offered to obtain different kinds of renewable energies. Among them, biomass can be considered as a promising form of energy source, which is known as the greatest source of renewable energy. The estimated proportion of all kinds of renewable energy was 19.2% of global final energy consumption in 2014 [1]. Around 14% of all energy used in the world in 2014 was obtained from biomass. Among them, in 2015, around 77% of all used energy to generate heat was obtained from solid biomass [1]. However, in recent times, the importance of biomass energy has significantly grown in developed European countries [2-3-4-5-6]. Wheat, barley, rye, oat,

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maize, rice, canola, and sun flower are a variety of agricultural products the residues of which are considered to have a high potential from the bioenergy point of view of European Union [7]. The results show that the estimated crop residue resources in EU-27 could provide fuel for about 850 plants expected to produce about 1500 PJ/yr [7]. Other kinds of agricultural residues also have been investigated. Pellets of wood and oat husk have been compared in the production of gas fuel in a fixed-bed gasifier. In spite of the similarity in the composition and dimension of wood and oat husk pellets, the produced gas was completely different. Oat husk is not an acceptable fuel for gasification purpose (Plis and Wilk [8]). From the design point of view, the gasifiers are classified into two main categories: fixed-bed and fluidized-bed. Each of the mentioned gasifier reactors are of two types: updraft and downdraft. If the gasifier is fed from its upper side and syngas exits from the bottom, it is a downdraft gasifier. Usually, this type is technologically smaller and simpler. If the gasifier is fed from the upper side and the produced gas also comes out from the upper side of the gasifier, it is called an updraft gasifier [9].

Potato is a plant that is grown in more than 140 countries. The Food and Agriculture Organization (FAO) of the United Nations reported that the world production of potato in 2014 was about 385 million tons [10]. China, India and Russia are the biggest potato producers in the world [11]. Potato planting is also common in Iran [12]. About 330 million tons of potatoes are harvested from about 1.19 million hectares under potato cultivation in more than 140 countries of the world. After wheat, rice and corn, potato ranks fourth in the world in terms of area under planting [13]. Despite the fact that it is one of the major agricultural products in the world, potato stems and leaves (shoots) are considered as waste products because of a toxic content called solanine. As a result of this content, the huge amount of potato shoot that is produced is unfit for being used as a source of animal nutrition and cannot be used as fertilizer to restore soil. So, they are thrown away each year and farmers remove them from their farms [14]. Despite the huge land area that is under potato cultivation (around 1.19 million hectares), the enormous amount by-products from these fields in the form of potato shoots are considered useless and waste material [15]. But potato shoot can be a promising source of fuel energy. Using these plant tissues to produce energy will lead to the prevention of a lot of energy loss.

Gasification is considered an energy conversion process that not only has high efficiency but is also clean. This method is applicable to different kinds of feed stocks [16]. To achieve clean combustible gases, gasification can be used as an environmental friendly and advanced way to dispose of heavy fuel oils [17]. Moreover, it has attracted a great deal of attention in jointly solving the problems of meeting energy needs and waste disposal [18]. The air gasification of a pine wood block in the down draft gasifier was investigated. The hydrogen percentage in the mentioned study was reported as 21.18–35.39 mol% (molar percentage fraction of hydrogen in the produced gas) and it increased by increasing the temperature [19]. Hazelnut shell was also used as the feedstock to hydrogen production in air-blown gasification. The effect of moisture on fuel was considered in this research. The results illustrated that an increase of moisture in the fuel could increase the amount of combustible gases [20]. Zhao et al. tried air gasification on sawdust. A lab-scale gasifier was employed for this purpose in the mentioned research. The results showed a gasification efficiency of 56.9% [21]. Since gasification is a time and money consuming process, modeling the process before experiment could be helpful in managing the gasifier reactor, temperature, and evaluating the capability of the feedstock to produce high calorific value gases (Colpan et al. [22]). A new conceptual, integrated, two-stage biomass gasifier and solid oxide fuel cell system has been proposed and a multi-physics model for predicting the performance of this system has been developed. The electrical efficiency of the system has been found to be 25% and the fuel utilization efficiency, 44% [22]. The equilibrium model has been used to predict the gasification process in a downdraft gasifier for wood, paper, paddy husk, and municipal waste as feedstock. The effects of the initial moisture content of wood and the temperature of gasification zone on the calorific value have been investigated [23]. Increasing the moisture content left the amount of nitrogen and methane almost constant, while the amount of hydrogen and carbon dioxide increased, unlike carbon monoxide, which decreased with an increase in the moisture content. The calorific value of the wood decreased when the temperature was increased [23]. The thermodynamic equilibrium model is a capable method to simulate fuel production and can be useful in managing the effective factors in gasifier performance. However, the developed model in the current research was a temperature-based model, which, unlike the models presented in the literature, gave different outputs. Thus, it is not a fixed model and offers different results at different temperatures. Prediction of the syngas by a validated model can reduce the cost and time a researcher would spend to know by experiment. The main purpose of this research is to develop a validated model in order to predict the kind and amount of syngas produced by a fluidized-bed updraft gasifier, which is influenced by the feedstock, temperature, and the amount of air inlet.

Different objectives of this work include finding a new source of fuel and developing a thermodynamic equilibrium model. Optimizing the gasifier before use by modifying a validated model in case of temperature, ER, and other effective factors can lead to a great saving in time and energy in places where gasifiers are employed. In this work, potato shoot was used as the feedstock of a fluidized-bed updraft gasifier and a new source of fuel. A thermodynamic equilibrium model was also prepared to ease the work of the gasifier in later experiments and to know the experimental conditions in which the model worked more reliably. Literature review shows that different types of feedstock have been used for gasification purposes all over the world, although different factors must be weighed to consider a feedstock as a promising source of energy, such as the availability of the feedstock in variable climates in several parts of the world, the ability of the feedstock to release high calorific value gases, and an adequate availability of the feedstock in its places of access. In this study, potato shoot, with the mentioned conditions, was utilized as the feedstock with all specifications mentioned.

2.Material and method

The proximate and ultimate analysis was done on potato shoot as feedstock to obtain the input requirements of the model. The inputs of the model were moisture content, chemical formula of the feedstock, air inlet, and gasification temperature. By replacing the input data in the global gasification reaction formula and the solving of the related equations, the model was developed to predict the produced gas from the gasification reaction for potato shoot [23].

$$CH_xO_yN_z + m_wH_2O + X_g(O_2 + 3.76N_2) \rightarrow X_1CO + X_2H_2 + X_3CO_2 + X_4H_2O + X_5CH_4 + \left(\frac{z}{2} + X_g3.76\right)N_2 \quad (1)$$

where, $CH_xO_yN_z$ is the typical chemical formula of woody material based on a single atom of carbon. According to the results of CHN analysis, this formula for potato shoot is $CH_{1.747}O_{0.83}N_{0.074}$.

The kind and amount of syngas produced depends on the feedstock, ER, gasifier type and so on. The equivalence ratio (ER) is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. Stoichiometric combustion occurs when all the oxygen is consumed in the reaction, and there is no molecular oxygen (O_2) in the products. m_w is the amount of moisture content in each kilo mole of feedstock, which can be calculated as below [23]

$$m_w = \frac{24MC}{18(1-MC)} \quad (2)$$

According to a thermal gravimetric analysis (TGA) and the results of moisture content (MC) in this experiment for the potato shoot, $m_w = 1.65$. X_g is the amount of oxygen in each kilo mole of feedstock as calculated for potato shoot, it was X_g=0.06 and all X_i in the right side of global gasification reaction are unknowns which we are going to calculate them during this research. To calculate the five unknowns, five equations are needed, three of which could be obtained by using the mass balance for C, H and O, and the other two by using the thermodynamic equilibrium constants (K_1 and K_2). The first equation comes from the C balance in the global gasification equation

$$X_1 + X_3 + X_5 = 1 \quad (3)$$

Another equation is obtained from H balance

$$2X_2 + 2X_4 + 4X_5 = 1.747 + 2 \times 1.65 \quad (4)$$

The other equation could be achieved from the O balance in the global gasification equation

$$X_1 + 2X_3 + X_4 = 0.83 + 1.65 + 2 \times 0.06 \quad (5)$$

The methane formation reaction and the water gas shift reaction are as below, respectively

$$C + 2H_2 \leftrightarrow CH_4 \quad (6)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (7)$$

The fourth and the fifth equations are obtained from the equilibrium constants of methane formation and shift reaction

$$K_1 = \frac{n_{CH_4}}{(n_{H_2})^2} = \frac{X_5}{{X_2}^2} \quad (8)$$

$$K_2 = \frac{n_{CO_2} n_{H_2}}{n_{CO} n_{H_2O}} = \frac{X_3 X_2}{X_1 X_4} \quad (9)$$

The equilibrium constants can be obtained from the shift reaction and the methane formation as below [23]:

$$lnK_1 = \frac{7082.848}{T} + (-6.567)\, lnT + \frac{7.466 \times 10^{-3}}{2} T + \frac{-2.164 \times 10^{-6}}{6} T^2 + \frac{0.701 \times 10^{-5}}{2T^2} + 32.541 \quad (10)$$

and

$$lnK_2 = \frac{5870.53}{T} + 1.86\, lnT + 2.7 \times 10^{-4} T + \frac{58200}{T^2} + 18.007 \quad (11)$$

Since K_1 and K_2 are dependent on temperature (T) and their related equations are not linear, different constants could be achieved which among them the positive and non-imaginary results are acceptable.

On the other hand, the produced gas contents are investigated by a GC analysis. An updraft bench scale fluidized-bed gasifier was employed. The stainless steel reactor of the gasifier was 850mm high and its internal diameter was 50mm. It was equipped with thermocouples (T type) and a temperature indicator controller. The reactor was directly heated by an electrical furnace. Dried sand was utilized as the fluidized bed. The results of the proximate and ultimate analysis are shown in Table 1. The heater was turned on and it typically took around half an hour to stabilize at the desired temperature before starting each experimental run. Firstly, the potato shoot was pelletized. In order to obtain homogenous syngas, the pellets were fed into the gasifier three times at the rate of 0.166 kg/hour from the top of the gasifier. An air stream was introduced into the gasifier from the bottom. The airflow was under control using a rotameter in order to obtain the desired ER. The gasification experiments were done at five different temperatures: 650, 700, 750, 800 and 850°C, and two different ERs, 0.25 and 0.20. The produced gas passed through an ice-water condenser to transfer heat. Then the bio-oil was separated in a bowl floated in ice-water. After heat reduction, the gas went through a piece of cotton, on which the tar was collected. Silica gel was used to absorb the moisture content of the produced gas. Clean, cool, dry syngas was collected in gas bags after passing through the silica gel.

Table 1. Proximate and Ultimate Analysis of potato shoot

Proximate analysis	**(%)**
volatile matter	62.7
Fixed carbon	16.3
Ash	15.8
Moisture	5.25
Ultimate analysis	
Hydrogen	5.97
Carbon	41.65
Oxygen	48.88
Nitrogen	3.4
Sulfur	0.1

Afterwards, the results of the GC analysis were compared with the results of the modified model in order to validate the model. This model is a temperature dependent model, which means different outcomes would be achieved at different temperatures in the model. Therefore, the results obtained from each temperature in the model could be compared with the related data from the experiments.

3.Results and discussion

The main results of this study can be observed in Figs. 1 to 4. The temperature of the gasifier was kept between 650°C and 850°C, while other conditions were constant. Figure 1 shows the changes in percentages of each gas portion in the produced gas at ER=0.25. As Figure 1 shows, similar to the results of Zainal et al. [23], the amount of N_2 in the obtained syngases was more than other gases at all the temperatures. Its percentage decreased from 70% to 42% with increasing temperatures at ER=0.25. This trend could be explained by the secondary N_2-formation reaction from NO and char via nitrogen-containing surface species as an intermediate [24]. The percentage of H_2 showed an increasing trend (from 5.6% to 14.3%) when the temperature increased. The same trend was reported byMidilli et al. [20]. Likewise, H_2, the amount of CO_2 and CO increased gradually with increasing temperature. These achievements are in conformity with the results of the study of Ghani et al. [25]. Higher gas yields are expected due to enhanced liquid cracking and reinforcement of char reaction with the air blown into the reactor at higher temperatures. Many factors can be the reason of this increase with temperature, such as faster gas production due to initial pyrolysis, more endothermal char gasification reactions, and the cracking of heavier hydrocarbons and tar with increasing temperatures [27-28]. But, contrary to the results obtained from some other studies, rise in temperature was found to increase the amount of CH_4 from 4.4% to 9.5% [16-25]. After N_2, the amount of CO_2 is more than that of the others but their ranges are almost the same.

Figure 2 shows the changes in the composition of the syngas at different temperatures at ER=0.2. The percentage of CO_2 was not significantly affected by temperature, which was in agreement with the results of a study done by Ghani et al. [25]. The change in the gas composition for other gases was also negligible. Nevertheless, the greatest change was in case of H_2, which increased from 2.1% at 650 °C to 5.2% at 850 °C. The negligible variation of gas composition by changing the temperature at ER=0.2 and comparing it with the results at ER=0.25 could lead to the conclusion that temperature plays a more important role in the

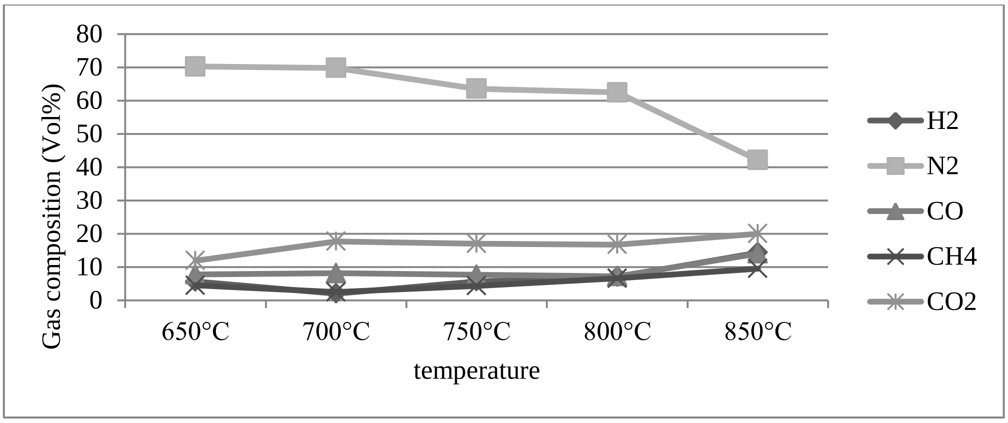


Fig.1.composition of the syngas at different temperatures at ER=0.25

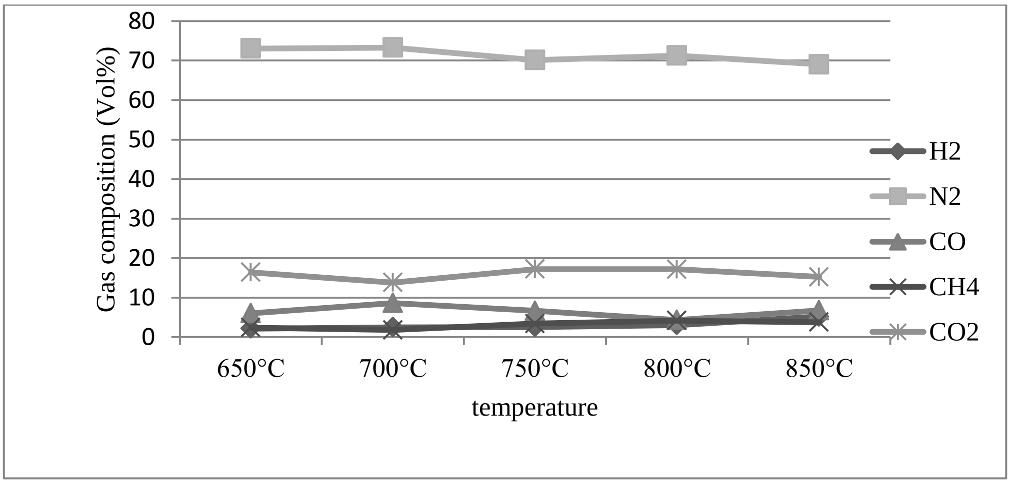


Fig.2. composition of the syngas at different temperatures at ER=0.2

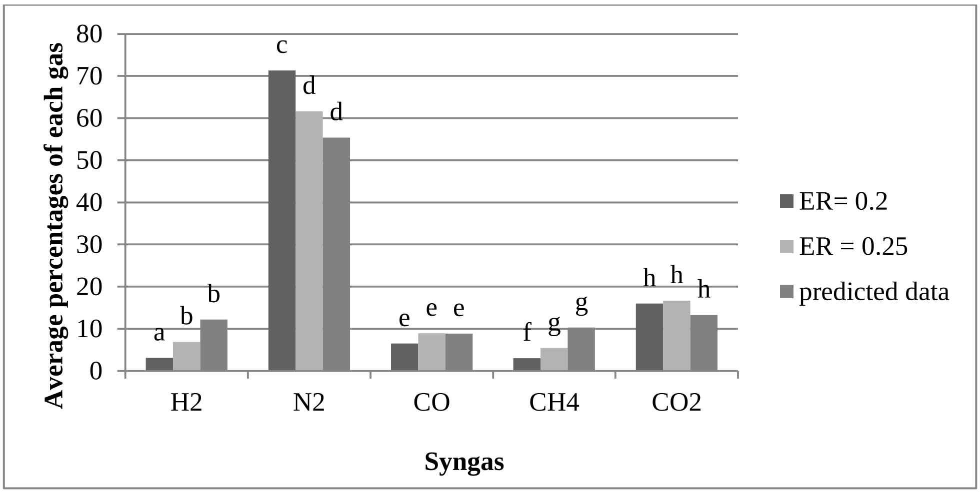
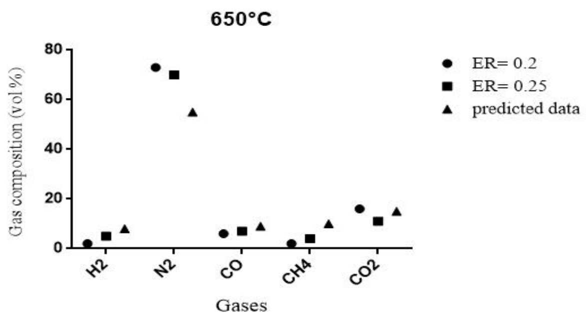
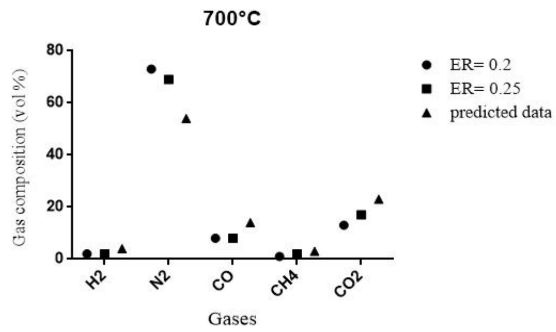


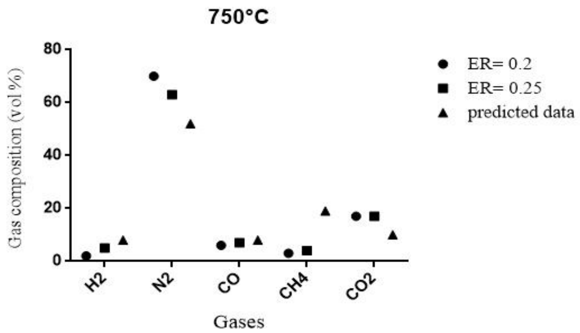
Fig.3. Comparing the average percentages of produced gases at ER=0.25 and ER= 0.2 with predicted data



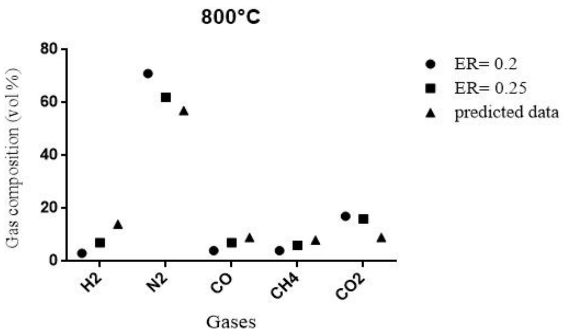
(a)



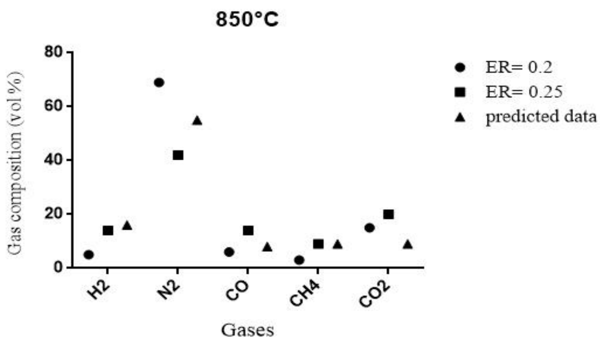
(b)



(c)



(d)



(e)

Fig.4.Comparing model results with experimental data (a) 650°C, (b) 700°C, (c) 750°C, (d) 800°C and (e) 850°C

gasification of potato shoot at ER=0.25 than 0.2.

The average percentages of each gas compared in Fig.3 at two different ERs. Better to say that in this figure the amount of lower calorific value gases and O_2 are not considered. The average amount of H_2 obtained from the model in Fig.3 is mainly more than experimental data at ER=0.25 and ER= 0.2, in contrary with N_2 which predicted data are mainly less than experimental data. CO shows better results in comparison with other syngases, specifically at ER=0.25 the average of syngas portion is really close to the predicted data. Similar to H_2, the average amount of predicted data for CH_4 is more than experiment results. To predict the amount of CO_2 the model could work better at ER=0.2 by looking at the average results. However, Fig.3 compares the average results with each other regardless of temperature; Fig.4 would discuss this subject separately with more details. Mainly the results observed at ER=0.25 were closer to predicted data. The best results in the mentioned situation were for CO with the error of just 0.7% following by N_2 with the error of 9% and CO_2 faced the error equals to 20%. Conversely, the average error to predict H_2 and CH_4 were somehow large (Simone et al. [29]). The relative average error for H_2 and CH_4 were 43% and 46%, respectively. The least error for the average portions of produced gases at ER= 0.2 was equal to 16% for CO_2. N_2 and CO, with a tolerable error of more than 20%, were at the next steps. In this case, similar to ER=0.25, the results for H_2 and CH_4 did not reach a good agreement with predicted data.

In order to realize the validity of the model statistically, analysis of variance (ANOVA) in the LSD method was employed. From a statistical point of view, as it can be seen in Fig.3, for H_2 the results obtained from the model and experimental data at ER=0.25 were the same and there was no significant difference between them, unlike for ER=0.2. Similar to H_2, according to ANOVA for N_2, the difference between the predicted data and experimental data at ER=0.25 was not significant and could be considered reliable. The difference between the predicted and experimental data at both ERs was negligible for CO and CO_2. Therefore, from the statistical point of view, the model was valid for predicting these product gases for the both ERs. According to this analysis, like for H_2 and N_2, the model results for CH_4, too, were not significantly different from the experiment results at ER=0.25, but different from the experiment results at ER=0.2. When ER increased from 0.15 to 0.25 in the study done by Doranehgard et al., syngas yield and hydrogen yield had an increasing trend, rising from 2.1 to 2.45 Nm^3/kg biomass and 37–41 g/kg biomass respectively. In this case, the results of the mentioned research are in agreement with the results of the current study. In the second stage, ER ascended from 0.25 to 0.3, where the hydrogen yield decreased, which is not in compliance with the results obtained from gasification of potato shoot [30]. In contrast to the mentioned results in the current study, an increase in the ER decreased fuel gases and lowered the heating value (LHV) in the research done by Monteiro et al. [31]. In the study done by Sales et al. the ER was calculated using mass balance. They reported an optimum ER of less than 0.412, which confirmed the ERs used in the current study [32].

ER can affect the gasification process. Increasing the ER increases the air in thereactor, leading to a rise in the gasification temperature, which can accelerate the process, thus improving the product quality [33]. To complete the validation of the model, all experimental data were compared with the model's results one by one. Figure 4 shows the results of this comparison separately at each temperature. Comparing the results of the experimental data at two ERs with predicted data by the model shows that the predicted data give valid results at 650°C, especially closer to GC analysis for ER=0.25. The predicted result for N_2 showed a lower amount than the experimental data for both ERs. Therefore, as shown in Fig. 4 (a), at 650°C the model result seems not to be close enough for predicting N_2. For all produced gases, the errors at ER=0.25 were less than the errors at ER=0.2 except for CO_2, for which the error to predict the gas amount at ER=0.2 was 7%, while this error was 21% at ER=0.25. Therefore, the developed model would be more reliable for ER=0.25 at 650°C. At 700°C, too, the amount of N_2 predicted was less than the actual data but the error was not very large but 22% at ER=0.25. However, the model's predicted results are close enough to the experimental data for other gases to be considered as valid results. As Fig.4(b) demonstrates, at 700°C, the results of the model for N_2 and CO_2 are more reliable than the other syngases. Figure 4(b) shows, like the results of the study done by Xie et al. [16], the amount of CO_2 increases as ER is increased.

Despite the fact that the obtained results from the model for 750°C at ER=0.25 are reasonable for CO, CO_2, and N_2, with the errors equal to 6%, 12%, and 17%, respectively, it does not seem valid for other gases. These errors at ER=0.25 were 19%, 13% and 24% respectively. The model predicts less N_2 and CO_2 than the experimental data for two ERs, but overestimates the amount of CH_4, CO, and H_2 beyond the actual data at 750°C (Fig.4[c]). Figure 4(d) demonstrates that the model's closest results to experimental results for N_2 happened at 800°C and ER=0.25 with an error of 7%, and the model is the most valid to predict this syngas under this condition. The results for the mentioned situation for CO, CO_2 and CH_4 with the related errors of 20%, 17%, and 25% look reliable but not good enough to predict H_2. According to Fig.4(e), the model works well mainly for ER=0.25 at 850°C. As the figure shows the obtained results for CH_4 from the model to be exactly the same as the results of experimental data at ER=0.25 and 850°C, the results for other syngases under this condition seem valid also, except for CO_2, which shows a greater difference than other syngases from the predicted data for both ERs. The amount of CO_2 in the produced gas clearly increases by increasing ER similar to the results of other studies [16]. The obtained results from the model for N_2 is almost an average of the experimental results for ER=0.2 and ER=0.25. ER can affect the gasification process due to two reasons. An increase in ER can increase the gasification temperature, which leads to faster oxidation reaction and, consequently, better product quality. On the other hand, in lower ERs, the reaction will encounter lower oxygen to complete the gasification reactions [25]. The reason for an increase in H_2 and CO proportions in the produced gas with an increase in ER can be thermal cracking of hydrocarbons and tars at higher temperatures [34].

Generally, the average error of the model decreased when the temperature was increased and the error calculated for 800°C and 850°C was less than the error observed in lower temperatures. Moreover, the average error in all temperatures in this study at ER=0.25 was less than ER=0.2. As a result, the developed model is more suitable for being used at ER=0.25 and higher temperatures since it is more reliable under these conditions.

The produced gas reached the maximum high heating value (HHV) at 850°C equal to 3.02 MJ/Nm^3 at ER=0.2. As Table 2 shows, HHV is favored by an increase in the gasifier temperature. In a typical biomass gasification process, when the temperature increases, the H_2 and CO will increase due to gasification reactions that occur simultaneously during the process, thus causing an increase in HHV, as the H_2 and CO have a major role in the equation [34]. The proportions of char, oil, and tar were 18.7%, 3.4% and 0.4%, respectively. Carbon conversion efficiency (CCE) showed a maximum value, 81.32% at the temperature of 850°C. In this study, an increase in temperature also leads to an increase in CCE. Additionally, when temperature increases, the CCE also increases, as a high temperature provides a high degree of combustion, which converts most of the organic matter of biomass to syngas [33].

In compliance with ER=0.2 at ER=0.25, the highest HHV was observed at 850°C and an increasing rate was seen for HHV by increasing temperature with 17%, 5.7% and0.6% char, oil and tar, respectively. Under this condition, HHV was 7.39 MJ/Nm^3. In contrast to ER=0.2, Table 3 shows the highest amount of CCE for ER=0.25 at 650°C, but, like the results of ER=0.2 for other temperatures, an increase in temperature leads to increasing CCE. In most of industries such as agriculture generating and consumption of energy is of a great importance [35]. A comparison of the results shown in Tables 2 and 3 indicates that HHV and CCE increase with increases in ER at all temperatures. Against the mentioned results, the gas calorific value decreased after increases in ER in the work done by Doranehgard et al. [30].

4.Conclusion

According to GC analysis on produced gas of potato shoot gasification, these tissues have a

Table 2. Effect of temperature on HHV and CCE at ER=0.2

Temperature	**650°C**	**700°C**	**750°C**	**800°C**	**850°C**
HHV(MJ/Nm^3)	1.99	2.12	2.53	2.6	3.02
CCE (%)	79.72	58	78.92	79.44	81.32

Table 3. Effect of temperature on HHV and CCE at ER=0.25

Temperature	650°C	700°C	750°C	800°C	850°C
HHV(MJ/Nm^3)	3.47	2.24	3.4	4.42	7.39
CCE (%)	83.04	77.68	79.96	81.88	82.96

great potential in the production of high calorific value gases. Considering the huge amount of potato cultivation in the world and the high calorific value gases such as H_2, CO, CO_2 and CH_4 produced from the gasification of potato shoot as seen in this study, this product can play a great role in energy generation. In view of the high costs of the gasification process, especially for analyzing the syngases and the time taken, specifically by small reactors, the obtained model would help significantly in the mentioned cases. A comparison of the model's predicted results with the experimental data demonstrates that this model can work under different conditions. The difference of this model with the models in other studies is that this model is based on temperature and is not a constant model. A comparison of the model's results with the experimental results having related temperatures also shows that the created model at 850°C has the maximum similarity with actual data compared to other temperatures. The most valid data was achieved at 850°C compared to the experimental data at ER=0.25 and 850°C. However, the obtained model for other temperatures for some of the syngases, discussed in previous section, gives acceptable results and would be useful. Considering the ANOVA analysis, the model is completely valid to predict all the produced gases at ER=0.25. Consequently, the model would be more suitable for used at ER=0.25 than ER=0.2.

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