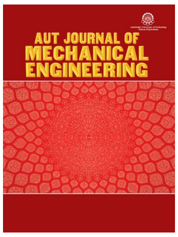


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# Evaluation of energy potential of municipal solid waste gasification in different regions of Iran by using a modified equilibrium thermodynamic model

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**ABSTRACT:** Municipal solid waste is the largest waste stream around the world and has a great potential for generating synthetic gas. An improved numerical model is used based on equilibrium thermodynamics to predict the composition of the municipal solid waste gasification products. To validate the superiority of the model, the results are compared and verified against some experimental studies. The developed model is then used to study the potential of energy extraction from solid waste in Iran as a case study. For this purpose, Iran is divided into ten separate zones, and the chemical composition of the wastes in each region is determined based on the type and amount of the waste compounds. Next, the effects of some important factors such as the amount of moisture content, environmental humidity, and equivalence ratio are investigated. The results show that at the equivalence ratio of 0.3, Khuzestan and Zagros regions have the highest and the lowest heating values of the produced synthetic gas with the cold gas efficiency of 20% and 16.5%, respectively. At the equivalence ratio of 0.6, the same qualitative results are obtained; however, the mentioned values of cold gas efficiency for Khuzestan and Zagros decrease to 14.8% and 13.8%, respectively.

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## 1- Introduction

Today, the use of solid wastes is an appropriate option for managing the growing demand for energy and the generation of solid wastes. However, only a few of the published studies are related to energy extraction from urban wastes [1]. Gasification of solid waste is a waste-to-energy conversion method that is beneficial from both energy production and environmental impacts points of view. Syngas as a product of the gasification process is mainly a combination of H2 ، CO2 ،CO ،CH4, H2O, and N2 species. It is used to produce bio-fuel for organic power plants [2]. Tar is another species of gasification products that has been attempted to be kept minimum due to problems arising from its production [3]. Various mathematical models have been developed to predict the behavior of the processes occurring during gasification. Among these models, the equilibrium models [3–5], One-dimensional kinetic models [2,6-7], and computational fluid dynamics models [8–10] have been widely used. Among these models, equilibrium thermodynamic models are common of interest due to fast prediction and ease of calculations. However, these models inherently have some problems in methane prediction [4].

The production rate and chemical composition of the wastes in each area are dependent upon factors such as geographical and climatic conditions. These factors should be considered before planning for the waste disposal system [11]. Nabizadeh et al. [12] showed that the amount of waste produced in Iran reached 28500 tons/day indicating the necessity of a system for solid waste disposal in this country. They divided Iran into ten regions and studied the rate of waste generation as well as the physical combination of the wastes in each region. The results of their studies are shown in Tables 1 and 2.

Many studies have been carried out to investigate the processes occurring during the gasification, and several equilibrium models have been developed for this purpose. Jarungthammachote et al. [4] used this model to predict the syngas content from the Municipal Solid Waste (MSW) in a downdraft gasifier. Their developed model was faced with some drawbacks in predicting the syngas species concentrations derived from gasification especially in CH4 and H2. This model was later improved by Barman et al. [3] with the addition of tar content to the products of syngas. Tar addition leads to compensate pre-mentioned defects to some extent, but still, there were differences between the results of numerical and experimental solutions.

Syngas is affected by different factors such as the operating condition of the gasifier. George et al. [13] studied the gasification process in vapor and vapor-air environments. The results of their studies show that inlet fuels with lower oxygen to carbon and higher hydrogen to carbon ratio have greater hydrogen production potential. Therefore, a higher heating value of syngas is expected from the gasification in the vapor environment. Cheng et al. [14] used the equilibrium model to simulate the gasification process of MSW. They considered

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**Fig. 1. Iran’s regions division**

air, steam, and hydrogen as three different environments for gasification. They concluded that the syngas produced from hydrogen environment has the highest heating value and the highest CO and H2 concentration.

Syngas production may also be affected by some other factors, including environmental humidity, biofuel Moisture Content (MC), Equivalence Ratio (ER), etc. [4,5,15]. Recently, equilibrium thermodynamic models have also been used to estimate the amount of pollutants from the gasification process. Shayan et al. [16] used the equilibrium thermodynamics model to study gasification of biomass from the first and second laws of thermodynamics viewpoints. In this study, the emission of pollutants from MSW was observed to be about 25% higher than that from wood. Also, this study showed that hydrogen production rate was higher in steam, oxygen and enriched oxygen environments, and the greatest amount of efficiency was obtained from gasification in the air environment.

This study is mainly concerned with the Cold Gas Efficiency (CGE), which is highly affected by the contents of H2, CO, CH4, in the products of the gasification process. To improve the previous studies the following objectives are followed:

• Investigation and classification of MSW production rate in different regions of Iran.

• Determination of the physical and chemical composition of the local wastes.

• Development of an equilibrium thermodynamic model for better prediction of syngas species.

• Investigation of the influences of different operational parameters effect such as ER, humidity, etc. on gasification process.

• Evaluation of the waste gasification potential and efficiency in Iran.

## 2- Investigation of the Solid Waste Composition in IRAN’s Regions

### 2- 1- Physical composition of IRAN’s MSW

The physical composition of wastes may differ for any region based on the geographical location and nutrition culture of that region. In this study, the same division of Nabizadeh et al. [12] study is considered as Fig. 1. In each region, the waste production rate and physical composition of the wastes have been determined for each area individually (see Table 1 and 2).

### 2- 2- Chemical composition of IRAN’s MSW

Most of the mathematical models, such as thermodynamic models and computational fluid dynamics models, need to determine the chemical composition of the input fuel. In this study, the method of Tchobanoglous [17] is used to estimate the chemical composition of solid wastes on a dry and ash-free basis. In their study, they considered the following approximate elemental distribution of the physical composition of the MSW as Table 3.

To check the validity of this method, the results of the present study are compared with the experimental data reported by Mohammadi et al. [18] for the case of the MSW composition in Urmia city, located at the northwest of Iran. Table 4 shows that the employed low-computational-cost approximate method acceptably predicted the MSW composition.

According to this, finally, Table 5 shows the proximate and ultimate analysis of each region’s MSW.

## 3- Governing Equations

The assumptions used in the present model are as follows:

• Chemical reactions of gasification occur under the equilibrium thermodynamic condition.

**Table 1. The production rate of MSW in Iran [12]**

| | Region | MSW production rate (tons/day) | Wet RDF production rate (tons/day) | Dry RDF production rate (tons/day) |
|---|---|---|---|---|
| 1 | Khuzestan | 2013.77 | 1731.04 | 1071.51 |
| 2 | Zagros | 2855.03 | 2633.77 | 1369.56 |
| 3 | Azerbaijan | 2527 | 2353.14 | 1362.47 |
| 4 | Khazar | 2440.5 | 2329.95 | 1220.89 |
| 5 | Khorasan | 2071.5 | 1831.83 | 1033.15 |
| 6 | Esfahan | 1832.16 | 1660.49 | 886.7 |
| 7 | IRAN South East | 1222.471 | 1074.67 | 657.7 |
| 8 | Tehran | 10959.59 | 10090.49 | 5448.9 |
| 9 | IRAN South Coast | 811.46 | 757.50 | 393.14 |
| 10 | Fars | 1680.13 | 1457.85 | 883.46 |

**Table 2. Results of data analysis of ten different regions [12]**

| | Fars | South East | South Coasts | Tehran | Isfahan | Khorasan | Khazar | Azarbaijan | Zagros | Kuzestan |
|---|---|---|---|---|---|---|---|---|---|---|
| Organic (%) | 64.1 | 62.55 | 78.98 | 74.56 | 76.3 | 70.96 | 77.72 | 67.34 | 78.24 | 60.92 |
| Paper and Card board (%) | 6.35 | 8.3 | 4.94 | 5.04 | 4.38 | 6.93 | 8.43 | 8.67 | 7.21 | 8.26 |
| Plastic (%) | 12.9 | 12.15 | 7.41 | 6.25 | 5.26 | 6.87 | 7.61 | 11.85 | 7.28 | 8.38 |
| Metals (%) | 2.27 | 3.05 | 2.4 | 2.48 | 2.9 | 2.36 | 0.89 | 2.25 | 1.71 | 4.42 |
| Rubber (%) | 1.32 | 1.9 | 0.4 | 1.11 | 0.97 | 0.74 | 0.47 | 0 | 0.52 | 3.24 |
| Textile (%) | 2 | 2.25 | 1.62 | 3.29 | 3.72 | 2.93 | 1.24 | 2.87 | 1.4 | 4.06 |
| Glass (%) | 0.23 | 2.25 | 1.89 | 2.03 | 1.71 | 2.27 | 0.91 | 1.81 | 1.94 | 4.11 |
| Wood (%) | 0 | 0.9 | 0 | 1.82 | 0 | 0 | 0.96 | 2.39 | 0.6 | 1.1 |
| Others(%) | 7.73 | 6.65 | 2.36 | 3.42 | 4.76 | 6.94 | 1.77 | 2.82 | 1.1 | 5.5 |

**Table 3. Elemental distribution of MSW in percent by weight [17]**

| Component | MC (%) | Percent by weight (Dry basis) C | H | O | N | S | Ash |
|---|---|---|---|---|---|---|---|
| | | | Organic | | | | |
| Food waste | 69.85 | 48 | 6.4 | 37.6 | 2.6 | 0.4 | 5 |
| Paper | 13.15 | 43.5 | 6 | 44 | 0.3 | 0.2 | 6 |
| Cardboard | 0 | 44 | 5.9 | 44.6 | 0.3 | 0.2 | 5 |
| Plastics | 0.34 | 60 | 7.2 | 22.8 | - | - | 10 |
| Textiles | 13.75 | 55 | 6.6 | 31.2 | 4.6 | 0.15 | 2.5 |
| Rubber | 0.89 | 78 | 10 | - | 2 | - | 10 |
| Leather | 0 | 60 | 8 | 11.6 | 10 | 0.4 | 10 |
| Yard waste | 0 | 47.8 | 6 | 38 | 3.4 | 0.3 | 4.5 |
| Wood | 20 | 49.5 | 6 | 42.7 | 0.2 | 0.1 | 1.5 |
| | | | Inorganic | | | | |
| Glass | 0 | 0.5 | 0.1 | 0.4 | 0.1 | - | 98.9 |
| Metal | 0 | 4.5 | 0.6 | 4.3 | 0.1 | - | 90.5 |
| Ash | 0 | 26.3 | 3 | 2 | 0.5 | 0.2 | 68 |

**Table 4. The comparison between the prediction of MSW composition in present study and experimental study [18]**

| | C | H | O | S |
|---|---|---|---|---|
| Present study | 29.07 | 45.1 | 15.63 | 0.061 |
| Mohammadi et al. [18] | 27.1 | 43.1 | 15.3 | 0.06 |

**Table 5. Proximate and ultimate analysis**

| | Proximate analysis (%wt) | | | | | Ultimate analysis (%wt) | | | | | HHV (MJ/kg) | LHV (MJ/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Region | Moisture | Volatile | Fixed carbon | Ash | C | H | O | N | S | (d.b.) | (d.b.) |
| 1 | Fars | 39.4 | 38.9 | 7.3 | 14.4 | 56.3 | 7.2 | 34.6 | 1.6 | 0.2 | 22.74 | 21.28 |
| 2 | South East | 38.8 | 40.4 | 7.5 | 13.3 | 55.7 | 7.2 | 35.3 | 1.6 | 0.2 | 22.45 | 20.99 |
| 3 | South coast | 48.1 | 35.9 | 8.4 | 7.6 | 53.7 | 7 | 37 | 2 | 0.3 | 21.61 | 20.19 |
| 4 | Tehran | 46 | 36.5 | 8.5 | 9 | 54 | 7 | 36.7 | 2.1 | 0.3 | 21.81 | 20.39 |
| 5 | Esfahan | 46.6 | 34.5 | 8.4 | 10.4 | 53.8 | 7 | 36.7 | 2.3 | 0.3 | 21.75 | 20.33 |
| 6 | Khorasan | 43.6 | 35.6 | 8 | 12.8 | 53.8 | 7 | 37 | 2 | 0.3 | 21.65 | 20.23 |
| 7 | Khazar | 47.6 | 38.2 | 8.5 | 5.7 | 53.3 | 7 | 37.7 | 1.8 | 0.3 | 21.36 | 19.94 |
| 8 | Azerbaijan | 42.1 | 41.6 | 8.1 | 8.2 | 54.3 | 7 | 39.6 | 1.6 | 0.2 | 21.77 | 20.35 |
| 9 | Zagros | 48 | 37.7 | 8.5 | 5.8 | 53.3 | 7 | 37.5 | 1.9 | 0.3 | 21.42 | 20.00 |
| 10 | Khuzestan | 38.1 | 38.7 | 7.6 | 15.6 | 56.1 | 7.2 | 34.6 | 1.9 | 0.2 | 22.85 | 21.39 |

• The process is adiabatic and there is no heat exchange with the surroundings.

• The wastes are comprised of C, H, O, N, S, and N atoms, and all N and S elements release as a stable molecule (i.e., N2 and SO2).

The elements in the biofuel can be expressed by a chemical formula of CHxOyNzSl. Where x,y,z, and l indexes can obtain from the ultimate analysis of fuel and the following equations [3]:

$$x=\frac{(H)M_C}{(C)M_H},\ y=\frac{(O)M_C}{(C)M_O},\quad z=\frac{(N)M_C}{(C)M_N},\ l=\frac{(S)M_C}{(C)M_S} \tag{1}$$

In Eq. (1) Mi refers to the molecular weight of species i. Regarding the above equations, the general form of gasification process reaction is shown in Eq. (2).

$$\begin{aligned} &CH_xO_yN_zS_l+w\left(H_2O\right)+ m_{ar}\left(O_2+3.76N_2\right)\rightarrow n_{H_2}H_2 \\ &+n_{CO}CO+n_{CO_2}CO_2+n_{H_2O}H_2O+ \\ &n_{CH_4}CH_4+n_{SO_2}SO_2+\left(\frac{Z}{2}+3.76m_{ar}\right)N_2 \end{aligned} \tag{2}$$

In this equation and refers to the molar coefficient of required air and moisture content respectively. Eq. (3) is used to calculate these parameters [18,19]:

$$\begin{aligned} m_{ar}&=ER.m_{as} \\ m_{as}&=\left(1+0.25x-0.5y\right) \\ w&=\frac{M_{biomass}\left(MC\right)}{M_{H_2O}\left(1-MC\right)} \end{aligned} \tag{3}$$

There are seven unknown species in Eq. (2) that need to be determined by seven equations. Five number of these equations are derived from the atomic balance of the inlet fuel.

$$\begin{aligned} &1-n_{co}-n_{co_2}-n_{CH_4}=0 \\ &x+2w-2n_{H_2}-2n_{H_2O}-4n_{CH_4}=0 \\ &y+w+2m_{ar}-n_{CO}-2n_{co_2}-n_{H_2O}-2n_{SO_2}=0 \\ &n_{N_2}-\left(\frac{z}{2}+3.76m_{ar}\right)=0 \\ &1-n_{SO_2}=0 \end{aligned} \tag{4}$$

Another two equations are derived by considering the two chemical equilibrium constants as functions of temperature (T) [3].

Water-Gas Shift Reaction (WGSR):

$$\begin{aligned} &CO+H_2O\rightarrow CO_2+H_2 \\ &K_1=\frac{n_{CO_2}n_{tot}}{n_{CO}n_{H_2O}}=\exp\left(\left(\frac{4276}{T}\right)-3.961\right) \end{aligned} \tag{5}$$

Methanation Reaction (MR):

$$\begin{aligned} &C+2H_2\rightarrow CH_4 \\ &K_2=\frac{n_{CH_4}n_{tot}}{n_{H_2}n_{H_2}}= \\ &\exp\left(\begin{aligned} &\frac{7082.842}{T}-6.567\times\ln T+\frac{\left(7.467\times10^{-3}\right)\times T}{2} \\ &-\frac{2.167\times10^{-6}}{6}\times T^2+\frac{0.702}{2\times T^2}+32.541 \end{aligned}\right) \end{aligned} \tag{6}$$

### 3- 1- Energy balance

The temperature of the gasification zone is needed to calculate the equilibrium constants of Eqs. (5) and (6). For this purpose, the energy balance relation is used in adiabatic condition. When the gas temperature is equal to T and air inlet temperature is equal to 298 K, the energy balance equation is written as following [4]:

$$\sum_{j=react}\bar{h}^o_{f,i}=\sum_{i=react}n_i\left(\bar{h}^o_{f,j}+\Delta\bar{h}^o_{T,i}\right) \tag{7}$$

where $\Delta\bar{h}^o_{T,i}$ refers to the formation enthalpy difference between the given condition and reference condition. Eq. (8) is used to calculate this parameter.

$$\Delta\bar{h}^o_{T,i}=\int_{298}^{T}\bar{c}_p dT \tag{8}$$

$\bar{h}^o_{f,i}$ in Eq. (7) are determined from Tables 4 for each species.

Table 6 gives the formation enthalpy of various species including in the gasification process.

The enthalpy of formation of input fuel calculates from Shabbar et al. [21] study by using Eqs. (9) and (10).

$$\bar{h}^o_{f,biomass}=HHV-\left(\frac{x}{2}\right)\times285830-393546 \tag{9}$$

**Table 6. Formation enthalpy of various species including in gasification process**

| Species | $\bar{h}_f^o$ ($\frac{\text{kJ}}{\text{mol}}$) |
|---|---|
| CO | -110.5 |
| $CO_2$ | -393.5 |
| $H_2O$ | -241.8 |
| $CH_4$ | -74.8 |
| $SO_2$ | -296.8 |

$$HHV = 0.3491(C) + 1.1783(H) + 0.1005(S) - 0.1043(O) - 0.0151(N) - 0.0211(Ash) \quad (10)$$

$$(LHV)_{fuel} = HHV - 9[H]h_{fg}$$

The LHV of syngas is used to estimate the gasification efficiency of solid fuels which calculates by Eq. (11) [4].

$$LHV = \frac{(107.98[H_2] + 126.36[CO] + 358.18[CH_4]}{1000} \quad (11)$$

In the above equation [H2], [CO] and [CH4] refer to the mole fraction of syngas species.

### 3- 2- Model improvement

Previous studies have shown that the drawbacks in estimating the syngas species can be due to simplifying assumptions of the model, such as the ideal gas assumption and absence of the Tar species [4]. Different methods have been used by different researchers to overcome this problem [4,21]. In the present work, the method described in the Mendiburu et al. [19] study is used to improve the model to better predict the methane content in syngas composition. As described in Sec. 4.2, this modification improved the prediction of syngas composition as compared with previous studies [3]. In this method, the volume percentage of methane in the syngas is calculated by regression between experimental data. Eq. (12) shows the methane percentage regression relation used in the study of Mendiburu et al. [19].

$$P_{CH_4} = 6.6799 + 8.6328X_1 - 7.4106X_2 - 3.1582X_3 + 1.5183X_1X_2 - 8.9410X_1X_3 + 5.5317X_2X_3 \quad (12)$$

In the above equation, the hydrogen in the fuel to the humidity ratio ($X_1$), the equivalence ratio ($X_2$) and average gasification temperature ($X_3$) are calculated from Eq. (13).

$$X_1 = \left(\frac{x_H}{M_{H_2O}w}\right)$$

$$X_2 = \left(\frac{ER}{0.35}\right) \quad (13)$$

PCH4 in Eq. (12) is the volume percentage of methane in syngas and can be converted to molar content according to Eq. (14) [19].

$$X_3 = \left(\frac{T}{900}\right)$$

$$n_{CH_4} = \frac{P_{CH_4}}{400}\left(\frac{\eta_{CC}x_C + \frac{x_H}{2} + w + \frac{x_N}{2} + 3.76m_{ar}n_{H_2O}}{1 + \frac{P_{CH_4}}{80}}\right) \quad (14)$$

## 4- Results and Discussions

The results are presented in two subsections. After the validation of results, first, the potential of biogas production from MSW in the ten regions of Iran is investigated. This can help to decide on the development and creation of biogas production units. Next, the effects of operational and environmental conditions on gasification efficiency are studied.

### 4- 1- Numerical method and validation

Fig. 2 shows the calculation algorithm used in this work. To get the values of $n_{H_2}$, $n_{CO}$, $n_{CO_2}$, $n_{H_2O}$, $n_{CH_4}$ and $n_{SO_2}$ by assuming and initializing the initial temperature (T) within Eqs. (5) and (6) the initial values of $K_1$ and $K_2$ were calculated. Then with simultaneous solving the Eqs. (4) to (14),

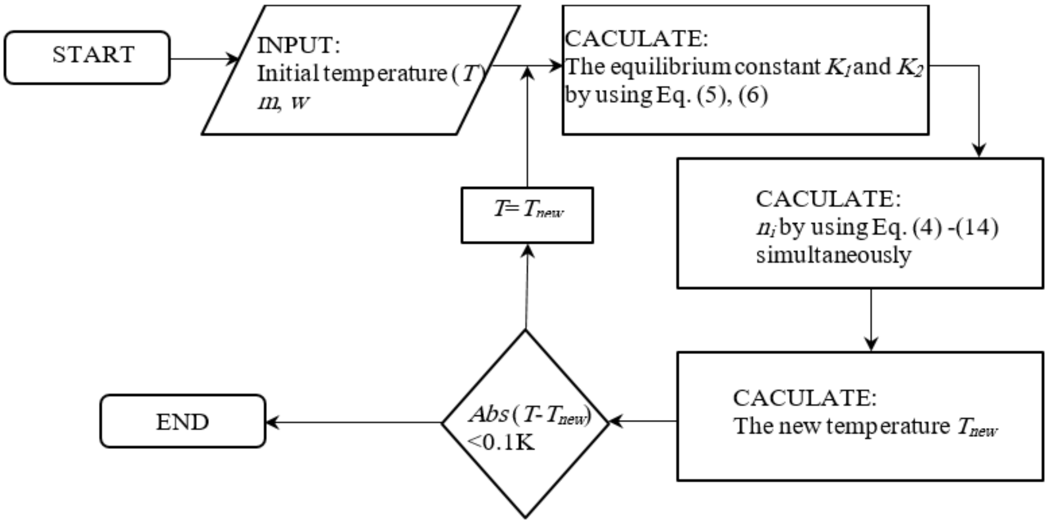



**Fig. 2. Calculation algorithm used in the present study**

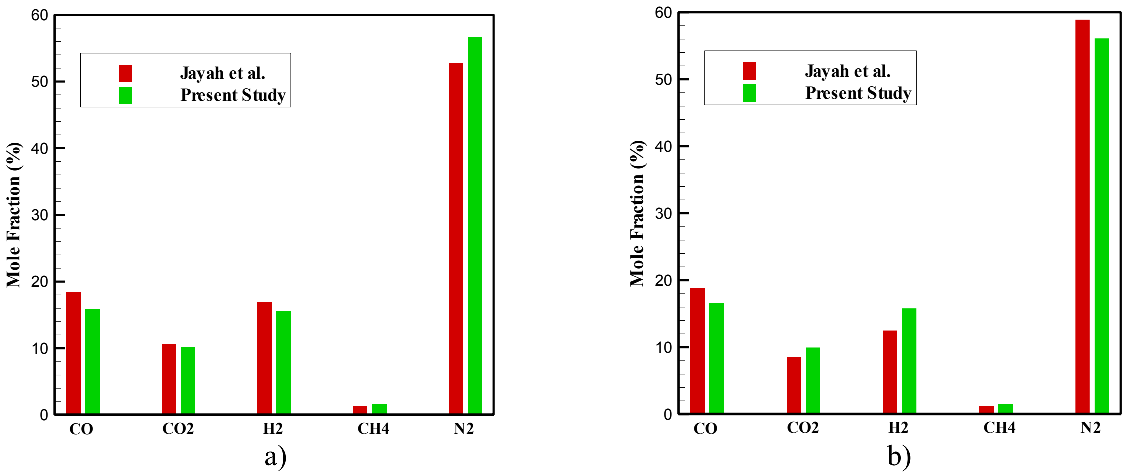



**Fig. 3. Comparison of the results of the present study with experimental data [3] a) ER=0.433, MC=16% b) ER=0.427, MC=14%**

the unknown parameters are calculated by Newton-Raphson's method. Engineering Equation Solver (EES) software is used to solve all governing equations with acceptable precision.

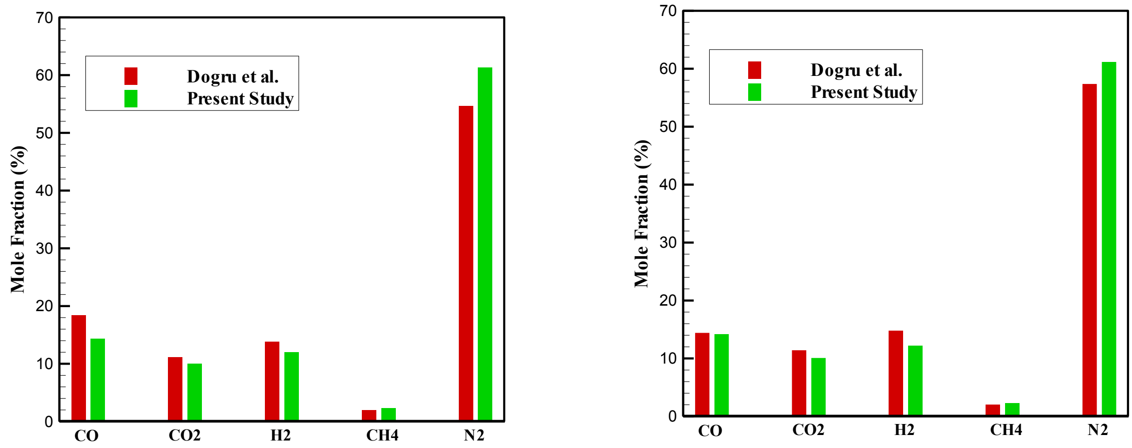
For validation, the results of the currently modified model are compared with some experimental studies. The results are shown in Figs. 3 and 4. According to Fig. 3 (a) and (b), the present model predicts the syngas composition with Root Mean Square (RMS) errors of about 2.18 and 2.3 for the ER of 0.433 and 0.427, respectively.

In Figs. 4 (a), (b) the present model is compared with the experimental study of Dogru et al. [23] for the air to fuel ratio of 1.37 and 1.38. This shows that the present model predicts the syngas composition with average RMS errors of 3.61 and 2.14 respectively.

Gasification temperature is another key parameter in the validation of the gasification process. Table 7 compares the predicted temperature in the present work with experimental data reported in references [3,22].

## 4- 2- Efficiency evaluation and MSW gasification potential

The Low Heating Value (LHV) of dry residue is used to evaluate the energy production potential from MSW. For this purpose, just the organic portion of the waste such as paper, plastic, wood, textiles, etc. is considered. According to Ouda et al. [24] study, Power Generation Potential (PGP) and the Net Power Generation Potential (NPGP) are calculated from Eq. (15).




a) b)

**Fig. 4. Comparison of the results of the present study with experimental data [23] a) A/F=1.37, MC=12% b) A/F=1.38, MC=12%**

**Table 7. Comparison of predicted temperature in K with experimental data**

| Present Study | Exp. | Err. (%) | Ref. |
|---|---|---|---|
| 1265 | 1400 | 9.6 | [23] |
| 1272 | 1300 | 2.1 | [23] |
| 831 | 851 | 2.3 | [3] |
| 824 | 762 | 8.1 | [3] |

$$PGP\left(\frac{\text{MW}}{\text{day}}\right)=\frac{\left(Dry\,waste\left(\frac{\text{kg}}{\text{day}}\right)\times Waste\;LHV\left(\frac{\text{kW}}{\text{kg}}\right)\right)}{1000} \tag{15}$$
$$NPGP\left(\frac{\text{MW}}{\text{day}}\right)=\eta\times PGP$$

$\eta$ in the above equations is considered to be 18% for the Residual Derived Fuel (RDF) [24]. Fig. 5 shows the energy production potential resulted from MSW for different regions of Iran. According to this figure, the Tehran region has the highest NPGP (around 231.46 MW per day) among the ten regions due to the high rate of waste production. Azerbaijan and Zagros regions with the NPGPs of 57.76 and 57.06 MW rank next in terms of energy production potential. As previously stated, these factors are not a unique criterion for the evaluation and classification of an RDF in different areas alone.

In addition to the above issues, another important factor is the Cold Gas Efficiency (CGE). CGE can be calculated through Eq. (16) [20].

$$CGE\,(\%)=\frac{SYNGAS\;LHV}{feed\;stock\;LHV}\times 100 \tag{16}$$

Fig. 6 compares the syngas LHV and CGE in the range of ER's 0.3-0.6 for ten regions.

The reason for choosing the mentioned ratios is the decreasing behavior of the CGE by increasing the ER. Among the constituent materials in MSW, rubber, and plastics have higher effects on the heating value of syngas since they have greater contents of C and H and a lower content of moisture. In the different regions of Iran, the MSW is mainly comprised of food waste with high levels of MC and hence, has low thermal efficiency. As shown in Fig. 6(a), at ER of 0.3, Khuzestan, Fars, and South east regions have the most LHV values compared with other regions. It can be due to the high level of plastics in MSW in those regions. It is worth mentioning that an increase in ER causes the most important partial combustion species in the syngas to decrease; therefore, it leads to an LHV drop. According to Couto et al [25] the syngas produced from wastes often has low heating value and low thermal efficiency. Keeping this in mind, as shown in Fig. 6 the maximum range of the region's syngas thermal efficiency is 15% to 20% at the best (ER 0.3) and 10% to 15% in the worst condition (ER 0.6). These numbers vary in terms of the physical and chemical composition of the wastes of different regions. According to this figure, the Azerbaijan, Fars, Khuzestan, and the South east regions have the highest efficiency relative to the other regions which can

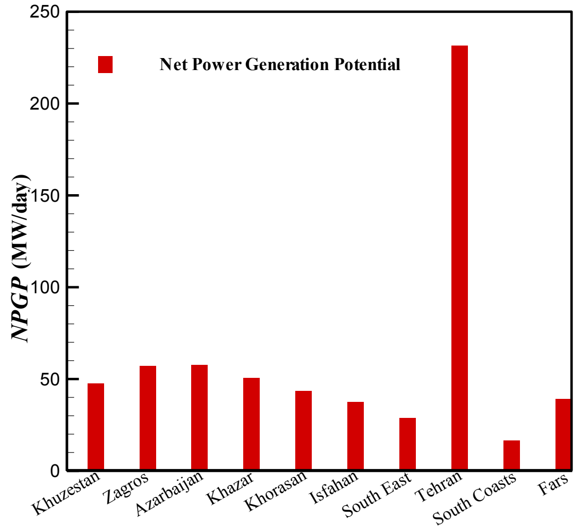



**Fig. 5. Evaluation of ten regions from the energy production potential stand point**

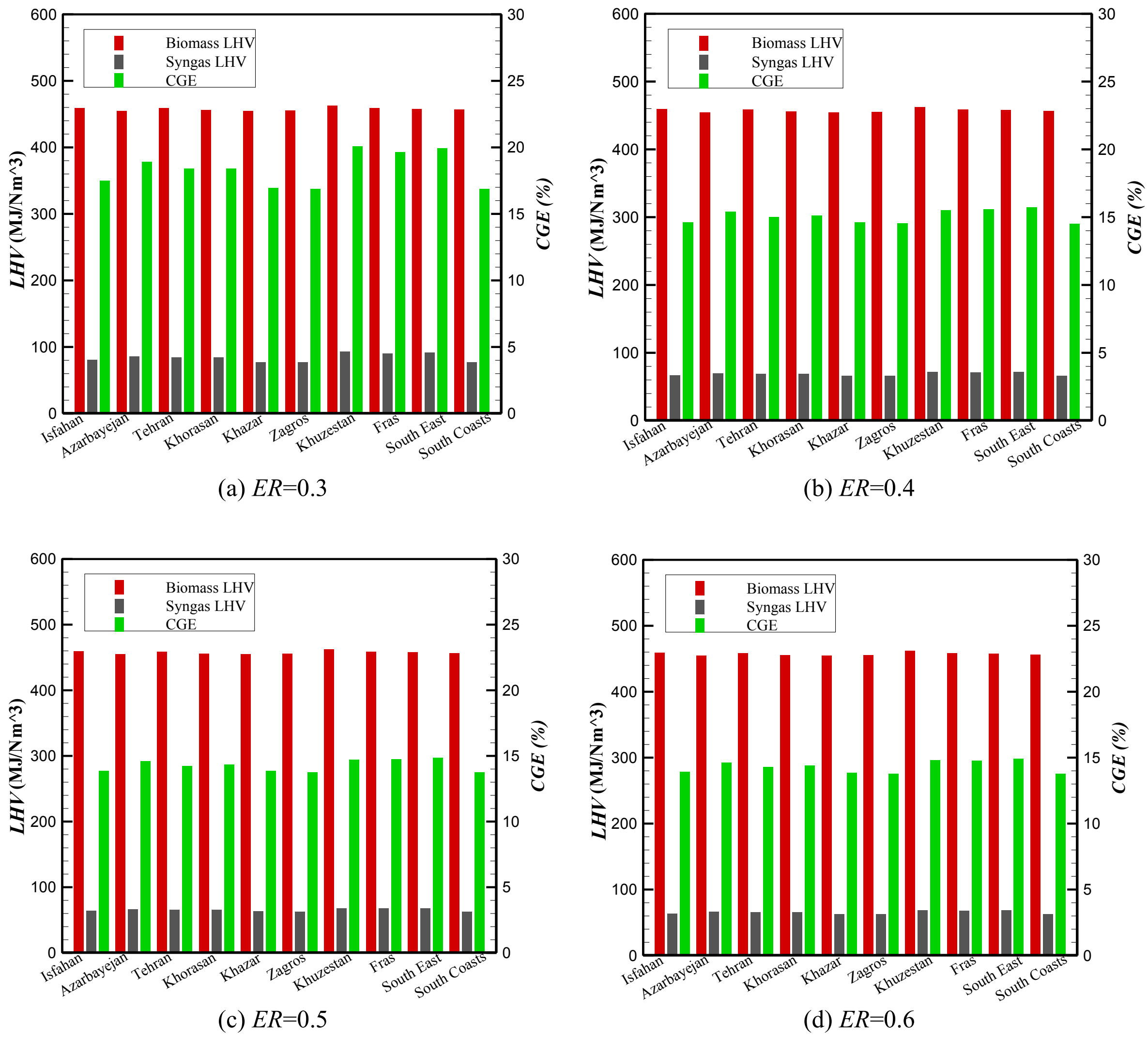
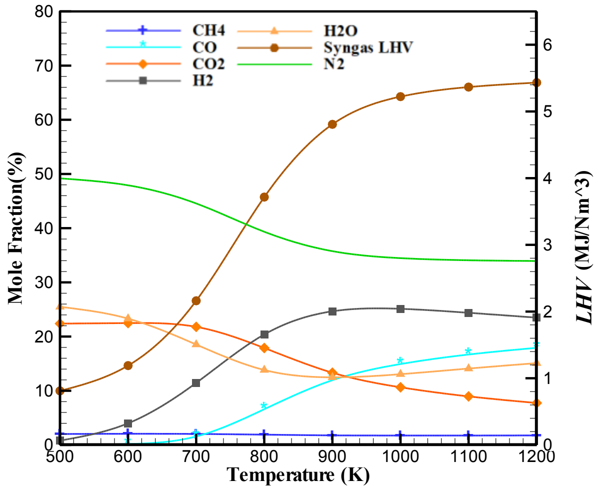
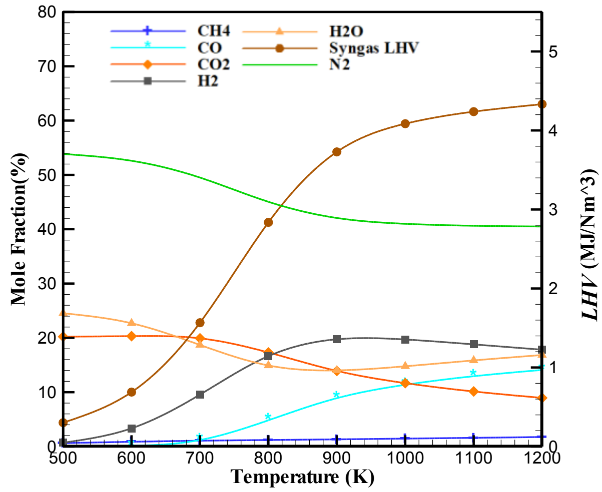


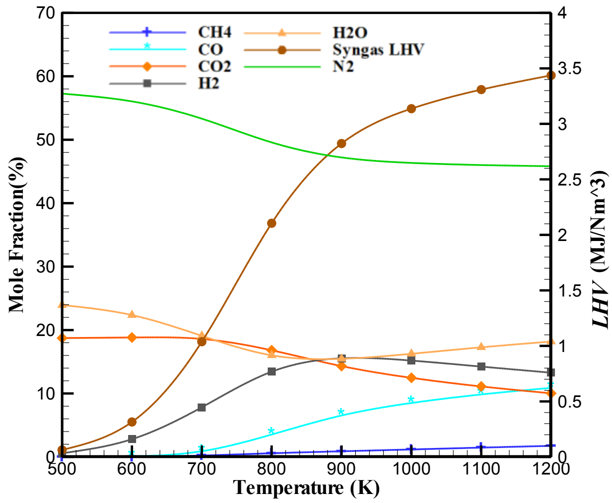

**Fig. 6. CGE comparison under a) ER=0.3 b) ER=0.4 c) ER=0.5 d) ER=0.6 in ten regions**



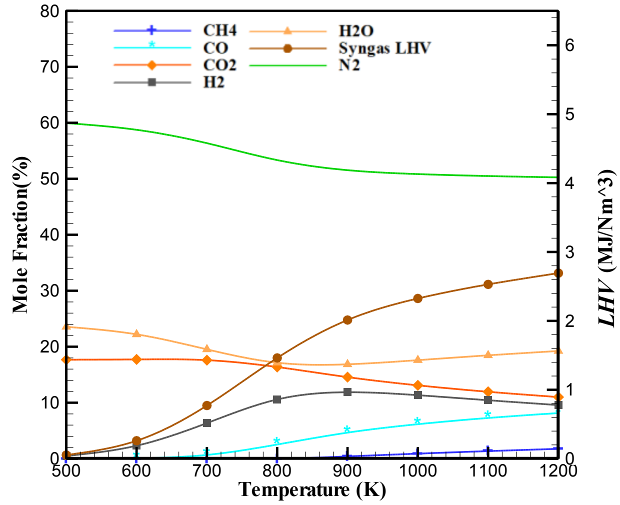

(a) *ER*=0.3




(b) *ER*=0.4




(c) *ER*=0.5




(d) *ER*=0.6

**Fig. 7. Effects of gasification temperature on species mole fractions and LHV a) ER=0.3 b) ER=0.4 c) ER=0.5 d) ER=0.6**

be effective in decision-making processes for locating biogas production units.

## 4- 3- Influence of operating conditions

ER, fuel MC, environmental conditions, and chemical composition of waste are major factors that can affect the production of syngas. The study of this section is limited to the Khuzestan area since other areas were observed to show similar qualitative trends.

### 4- 3- 1- Gasification temperature

Fig. 7 shows the effect of gasification temperature on the syngas composition and low heating value of Khuzestan region under different ER's. As shown in this figure, an increase in the gasification temperature leads to an increase in two important species in determining the LHV ($H_2$, CO).

We can justify these changes in accordance with the Le Chatelier's principle. According to this principle, any increase in temperature drives an exothermic reaction towards the reactants [26]. As shown in Fig. 8 in different ER's, up to a temperature of 700 K the methane reaction is dominant rather than water-gas shift reaction. This leads to a rapid rise in $H_2$. At a temperature above 700 K, the water-gas shift reaction prevails over methane production which leads to an increase in CO content.

### 4- 3- 2- Environmental temperature

Investigation of the weather maps shows that there is a sensible diversity in environmental humidity over the different

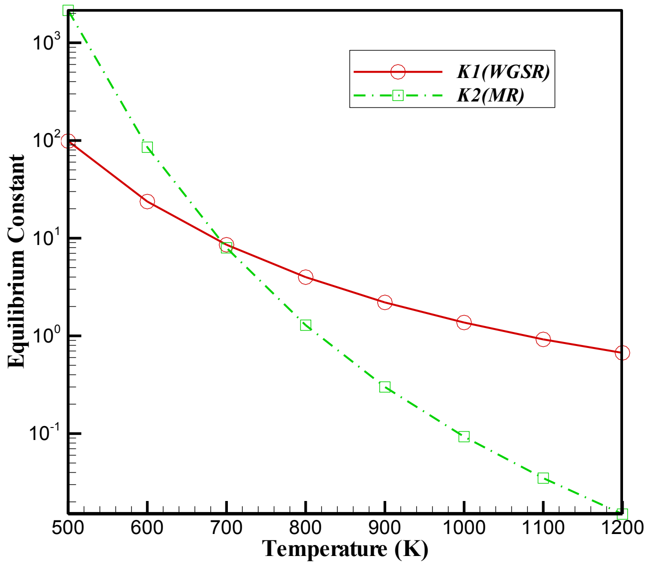



**Fig. 8. Equilibrium constants for methanation and water-gas shift reactions as a function of temperature**

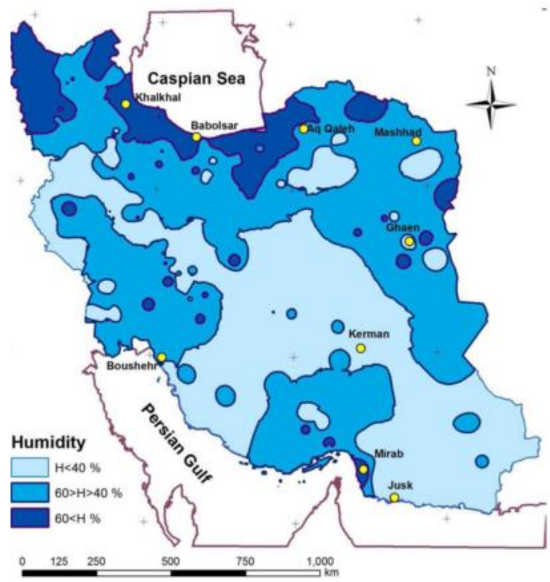



**Fig. 9. Relative humidity distribution in the different region [27]**

**Table 8. Average relative humidity distribution in different region of Iran**

| Region | *R.H* |
|---|---|
| Fars | 40 |
| South East | 40 |
| south coast | 60 |
| Tehran | 60 |
| Esfahan | 40 |
| Khorasan | 60 |
| Khazar | 90 |
| Azerbaijan | 60 |

regions of Iran. Yousefi et al. [27] classified the distribution of relative humidity in different regions of Iran into three different regions, as shown in Fig. 9. The values of average relative humidity in some different regions of Iran are quantitatively shown in Table 8.

Sharma et al. [7] proposed Eq. (17) to calculate the relative humidity of the environment. So:

$$R.H = \frac{\omega_{air}}{\omega_{air,sat}} = \frac{\omega_{air}}{P_{v,sat} M_{water} / P_a M_{air}} \tag{17}$$

In the above equation, water saturation pressure $P_{v,sat}$ is calculated from Antoni Eq. (18).

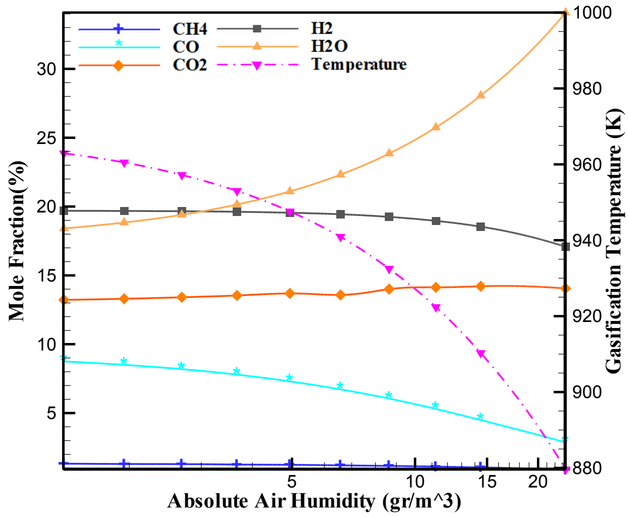
$$\log_{10}\left(P_{v,sat}\right) = A - \left(\frac{B}{T+C}\right) \tag{18}$$

where the A, B and C constant are as shown in Table 9.

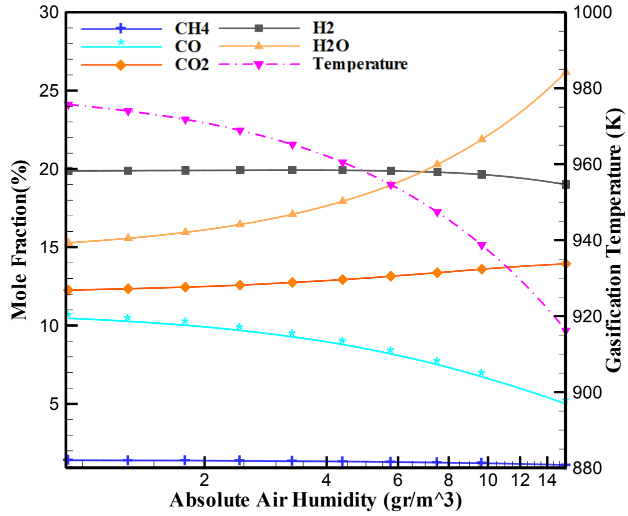
The LHV of syngas decreases with increasing humidity. This is due to the fact that more H2O content causes the amounts of effective species to decrease. As shown in Fig. 10 the environmental humidity has an adverse effect on the gasification temperature. For example, for Khazar region with the relative humidity of 90% (Fig. 10(a)), Khuzestan with the relative humidity of 60% (Fig. 10(b)), and Isfahan with the relative humidity of 40% (Fig. 10(c)), the gasification temperature of the gasifier dropped when the air humidity increased. As described

**Table 9. Antoni equation constants**

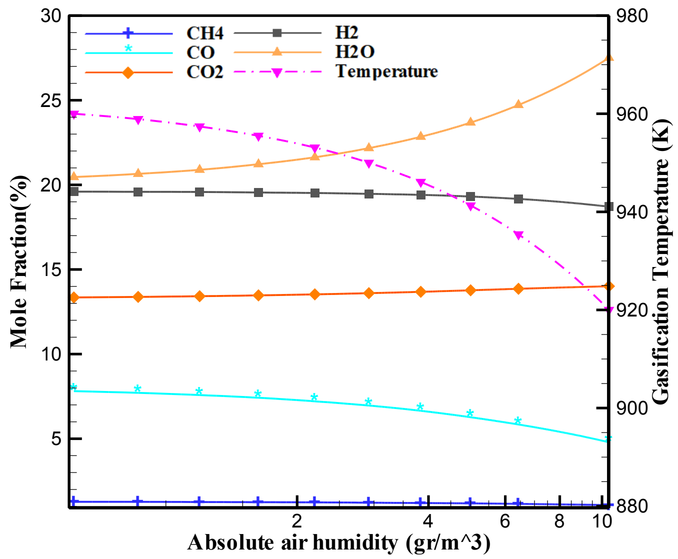
| Temperature range (K) | *A* | *B* | *C* |
|---|---|---|---|
| 255.8-373 | 4.6543 | 1435.264 | -64.848 |
| 379-573 | 5.5595 | 643.748 | -198.04 |




(a)




(b)




(c)

**Fig. 10. The effects of environmental humidity on gasification process for a)Khazar b) Khuzestan c)Isfahan region**

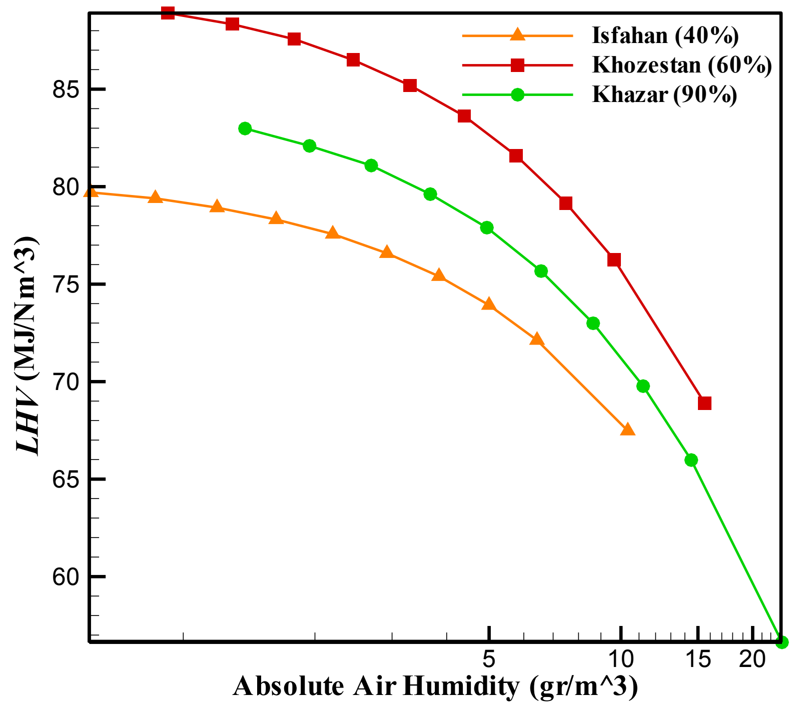



Fig. 11. The effects of environmental temperature on syngas LHV

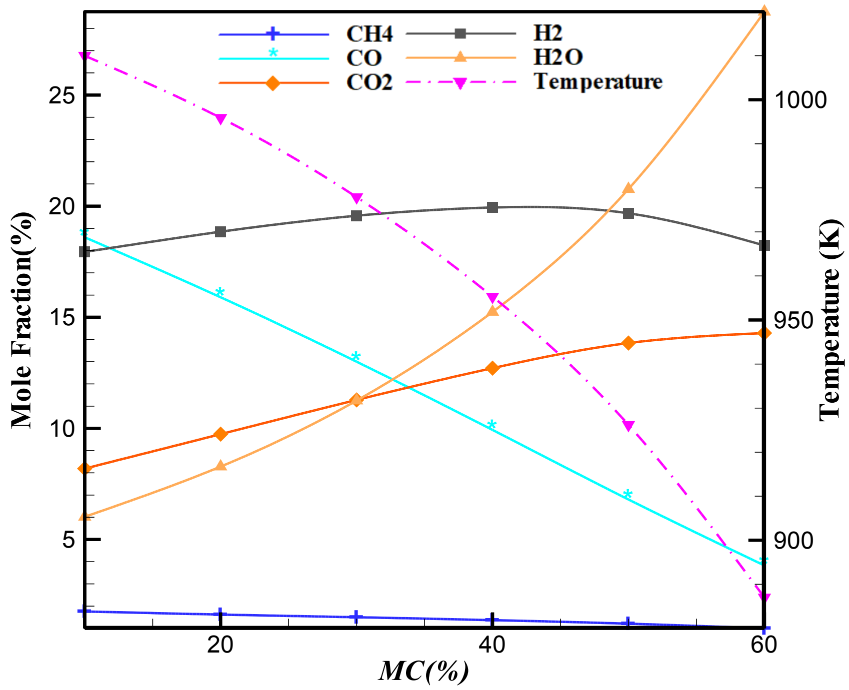



Fig. 12. effects of MC on syngas composition & temperature

before, the reduction in the temperature of the gasification due to the increase in the humidity causes the reduction of the molar fraction of the species which is influential in the heating value of the syngas. This will eventually lead to a reduction in the efficiency of the gasifier. Fig. 11 shows the effect of environmental humidity on syngas LHV.

### 4- 3- 3- Fuel moisture content

In the case of Iran, much of the solid waste is made up of food waste with the MC as the main part of it. In order to investigate the effect of fuel MC, the ER was kept to 0.4 and the impact of the increase of this parameter has been studied. As shown in Fig. 12 it is observed that an increase in MC leads to a slight

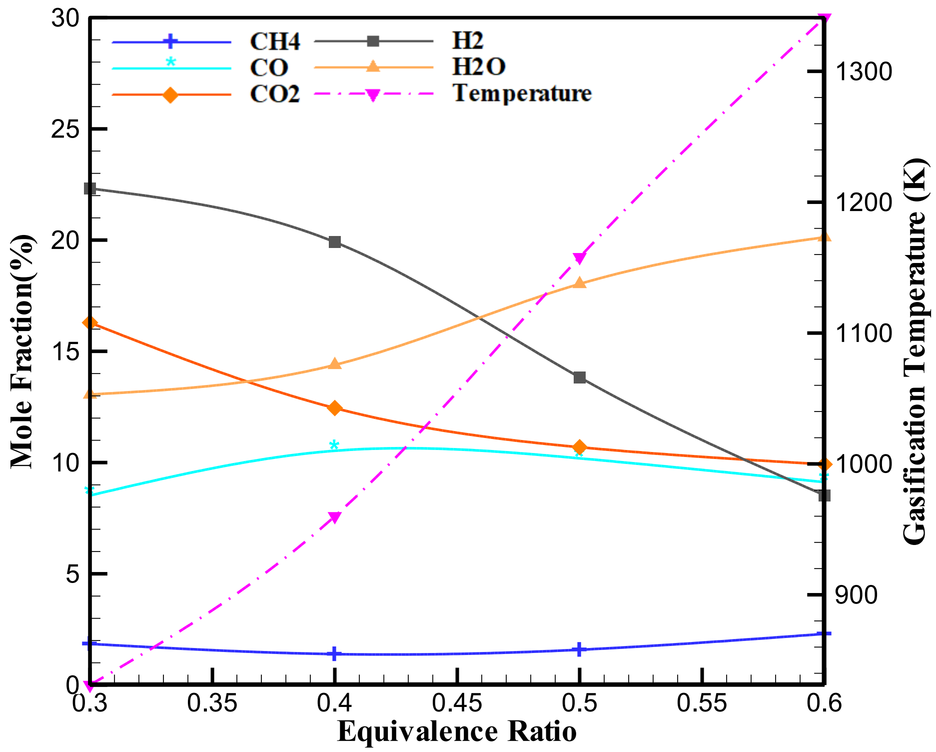



**Fig. 13. The effect of ER changes on the amount of syngas and temperature**

increase in H2 levels at a moisture content of 0.1 to 0.4. This is because any reduction in temperature leads to the progress of the WGSR reaction in the direction of H2 production due to the relative dominance of the WGSR reaction over the MR reaction in the specified temperature range in Fig. 12. After this, the H2 mole fraction diminished slightly due to the sharp increase in H2O. In the case of methane changes, the Linanki et al. [28] study shows that the variation of this species depends on the gasification pressure. Since the changes in the moisture content do not have a significant effect on the gasification pressure, so the level of changes in the methane concentration under different amounts of the fuel moisture can be ignored. The same behavior of CH4 changes has also been observed through the previous studies [5,29].

### 4- 3- 4- The equivalence ratio

Fig. 13 shows the effects of change in the ER on the amount of syngas production in the Khuzestan region. As shown in this figure, the increase of the ER from 0.3 to 0.6, caused the temperature to increase from 831 K to 1341 K. This increase has led to a decrease in H2 and CO2 levels by about 62% and 40% respectively and increase in CO level by about 16%. As mentioned previously, the methane content has a slight change with the ER.

## 5- Conclusions

In this paper, an improved thermodynamic equilibrium model was used to study the potential of energy extraction from municipal solid waste in Iran (as a case study). In this study, Iran was divided into ten separate regions and the chemical and physical compounds of solid wastes for each area were specified. The results were compared with some available experimental studies with acceptable precision. In summary:

- Tehran region with net power generation rates 231.46 MW/day had the greatest potential for producing and restoring energy due to the highest rate of waste production among the ten regions.
- Among all regions, Azerbaijan, Fars, Khuzestan, and the south eastern regions had the highest cold gas efficiency
- The range of cold gas efficiency changes from 15% -20% under the best condition and between 10%-15% under the worst condition for all regions.
- An increase in the gasification temperature led to the increase in the hydrogen and carbon monoxide fraction and, hence, synthetic gas heating value. On the contrary, this reduced the mole fraction of carbon dioxide and water.
- Increasing air humidity, as well as moisture content, had an adverse effect on the temperature of gasification, heating value, and cold gas efficiency.

• An increase in the equivalence ratio led to a reduction in the cold gas efficiency and the synthetic gas heating value due to the reduction in the mole fraction of effective species such as hydrogen.

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