Modeling and process design of municipal solid waste pyrolysis and gasification with a fixed-bed chamber

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Abstract. To design the process of municipal solid waste (MSW) pyrolysis and gasification in a fixed-bed more veritably and effectively, the modeling of this process was proposed based on Gibbs energy minimization by using the Aspen plus software. The proposed model was used to predict and analyze the influences of operating parameters including gasification temperature, air-fuel ratio and steam/MSW ratio on the composition, lower heating value (LHV), carbon conversion efficiency (CCE), heat conversion efficiency (HCE) and flammable gas contents (FGC) of syngas. The results indicate that there is a good agreement between the experimental data and the simulated data obtained using this model. The predicted appropriate gasification temperature was around 900℃ while the suitable air-fuel ratio was approximately 0.4, and the best steam/MSW ratio was around 0.4. A novel configuration of atmospheric fixed-bed chamber is designed for the municipal solid waste pyrolysis and gasification process based on the experimental and simulated results. The designed configuration was feasible with achieved heat balance of the system.

1. Introduction
With the improvement of urbanization and living standards, municipal solid wastes (MSW) output has grown at a speed of about 8~10% every year. In 2016, China’s rural living garbage output reached 160 million tons[1]. Due to the rural population living scattered, traffic inconvenience, the traditional treatment way is difficult to be implemented. The pyrolysis gasification technology on treating MSW has significant advantages including auxiliary fuel saving, effective reducing capacity, low investment and operation cost, and small covering area, which make this technology the development direction of rural MSW disposal instead of landfill, incineration and biodegradation[2-5]. The composition of MSW is variable due to the mixed collection and transportation, which leads to extremely complex pyrolysis and gasification process and simulating, complex mathematical models and iterative computations.

The thermodynamic equilibrium model based on Gibbs free energy minimization is suitable for this kind of simulation calculation of complex equilibrium system, because it does not require the knowledge of specific chemical reactions. Currently, researchers are using the Aspen plus software to establish reaction process models and solve computational problem, most of them are interested in combustion and gasification of coal and biomass. Based on Aspen Plus, Ramzan and co-workers...
design a steady-state model for biomass feedstock gasification[6]. Chen studied the effects of flue gas on the compositions and quality of syngas at various operating conditions[7]. Begum et al. had presented a numerical simulation model of a fixed-bed gasifier, and also used the Aspen plus software to analyze the gasification performance under varying operating parameters, such as air-fuel ratio, gasification temperature and moisture content of MSW[8]. These studies show the feasibility to get an appropriate operating parameters and conditions for MSW gasification with the Aspen Plus. However, efforts to optimize the practical engineering design implant the simulation are rare in the reported literature.

In order to design the process of municipal solid waste (MSW) pyrolysis and gasification in a fixed-bed more veritably and effectively, the modeling of this process was proposed based on Gibbs energy minimization by using the Aspen plus software in this paper. The proposed model was used to predict and analyze the influences of operating parameters including gasification temperature, air-fuel ratio and steam/MSW ratio on the composition, lower heating value (LHV), carbon conversion efficiency (CCE), heat conversion efficiency (HCE) and flammable gas contents (FGC) of syngas. Furthermore, a novel configuration of atmospheric fixed-bed chamber is designed for the municipal solid waste pyrolysis and gasification process based on the experimental and simulated results.

2. Model approach

2.1. Model establishment
There are no clearly boundaries between zones of combustion and gasification reaction for a fixed-bed gasifier[9]. Currently, the applicability using the single RYield module to describe the MSW pyrolysis section is limited. A RGibbs module in the Aspen plus was proposed to simulate gasification and combustion process of MSW since the R Gibbs module was proposed based on the chemical equilibrium and phase equilibrium limited by Gibbs free energy minimization, which can simulate decomposition, recombination and chemical reactions, and can predict the equilibrium composition of the produced syngas[10]. The process for gasification consists of three steps including drying, pyrolysis and gasification and combustion. A flow sheet of MSW gasification process was shown in Fig 1 (a). The MSW moisture is removed and exhausted from the separator in the first stage. In the second stage, the dried MSW is decomposed into volatile elements and char. Then the decomposed feed and air move to the last two stages.

![Figure 1](image)

Figure 1. (a) The flow sheet of gasification process based on fixed bed gasifier, (b) Aspen Plus simulation flowchart.

The simulation is developed with RYield, RStoic and RGibbs modules in Aspen plus. As depicted in table 1 and Fig 1 (b), RYield module simulates the evaporation of the MSW moisture in drying section. In drying section, the MSW moisture content is drained out and separated by a separator model Sep2 (module ID: SEP-1). Before MSW is fed into R Gibbs module, it can be decomposed into constituting components, which contain H2, O2, N2, carbon, sulfur, and ash. The pyrolysis section is
modeled by R Yield and R Stoic module, and Sep2 simulates the separation of char from syngas (module ID: SEP-2 and SEP-3). The decomposed MSW and gasification agents move to the R Gibbs reactor that has oxidation and gasification reactions. Peters et al. showed that R Gibbs models chemical equilibrium through energy minimization of Gibbs free[11]. By associating with the gasification and combustion (model ID: Q1, Q2), the heat of reaction is introduced by two heat stream into the R Yield reactor with drying and decomposition reactions. The outlet stream of R Gibbs reactor moves to Sep-4 module, and the residue is separated from it through specified split fractionation of the components.

### Table 1. Aspen Plus unit operation models illustration.

| Module ID | Aspen Plus ID | Function |
|-----------|---------------|----------|
| DRYING    | RYield        | Simulate the MSW drying based on the water content value according to the proximate analysis of MSW |
| PYROLYS   | RYield        | Yield reactor-converts non-conventional MSW into conventional components by using FORTRAN statement |
| CHAR-DEC  | RStoic        | The decomposition of char into carbon and ash is to deal with solid reaction in an easy way by simulating char gasification and combustion |
| GASIFY/ | RGibbs        | Gibbs free energy reactor handles three phase equilibrium and calculates composition of syngas based on the minimization of Gibbs free energy |
| BURN      |               |          |
| SEP-1...4 | Sep2          | Separate gas and solid |
| MX-EXCH   | Heater        | Mix product gas and provide the heat for pyrolysis-gas |
| MX-GASIN  | Mixer         | Mix gas feedstock |

#### 2.2. Assumptions

For simplification, some assumptions are made in this section. For example, this model is designed based on the hypothesis that it has enough stay time for chemical reactions to achieve an equilibrium state. And four basic assumptions in this model are: (1) The whole procedure is in stable mode, and its heat exchange is ideal in a fixed bed; (2) In state of equilibrium, there will be gasifier reactions without any pressure drop; (3) There are only carbon and ash in Char; ash is inert and has nothing with chemical reactions; (4) It only produced N2 forms, and there are no oxides of nitrogen. It assumes that tars are not equilibrium products and it can be used to simplify the hydrodynamic process.[12].

#### 2.3. Model equations

#### 2.3.1. Reaction equations

The average values of 10 major Chinese towns in recent years are used as the characteristic data of MSW in table 2. At the beginning, the gasification happens in the pyrolysis section, and then moves to the combustion section. It is shown in table 3, there are mainly four chemical reactions of water-gas shift, Boudouard reaction, combustion and methanation[13-14].

### Table 2. Characteristics of MSW.

| Proximate analysis (wt.%) | Ultimate analysis (wt.%) | Low heating value (kJ/kg) |
|--------------------------|--------------------------|--------------------------|
| MC: moisture content; A: ash; V: volatile matter; FC: fixed carbon; d: dry basis. | | 4951.2 |

### Table 3. Chemical reactions of gasifier

| Reaction number | Reaction name | Heat of reaction (MJ/kmol) |
|----------------|--------------|----------------------------|
| Endothermic reaction | C+CO2↔2CO | boudouard | +162.4 |
| R1            |             |                             |
| R2            | C+H2O↔CO+H2 | water-gas                  | +131  |
2.3.2. Calculation equations. Variation of LHV, HCE and CCE, FGC of syngas can be used to represent the gasifier quality of MSW gasification. CCE, LHV, HCE and FGC are defined as the following[15].

\[
\text{CCE}(\%) = \frac{\text{carbon content in the syngas} \times V_1}{\text{carbon content in the fed MSW} \times V_2} \times 100
\]

(1)

\[
\text{LHV (MJ/m}^3) = \frac{107.98 \times n_{H_2} + 126.36 \times n_{CO} + 358.18 \times n_{CH_4}}{1000}
\]

(2)

\[
\text{HCE (kJ/kg)} = \frac{Q \times V}{m_{MSW}}
\]

(3)

\[
\text{FGC(\%)} = \omega_{H_2} + \omega_{CO} + \omega_{CH_4}
\]

(4)

Where \( V_1 \) is mass flow rate of syngas, kg/hr, \( V_2 \) is flow rate of MSW, kg/hr, \( n_{CO}, n_{H_2}, n_{CH_4} \) are the mole percentages of those gases of syngas respectively, \( Q \) is the LHV of syngas (dry) yield in process of gasifier, kJ/m\(^3\), \( V \) is the volume of syngas (m\(^3\)), \( m_{MSW} \) is the weight of MSW fed into the system, kg, and \( \omega_{H_2}, \omega_{CO} \) and \( \omega_{CH_4} \) denote the compositions of corresponding gases in syngas respectively.

2.4. Model validation

The kitchen waste is the main component of MSW, and it has higher oxygen for LHV of syngas and CCE. As a result, it could select the kitchen waste to verify the validation of the model with the equivalence ratio 0.18. Then verifying the proposed model with experimental method reported by Niu et al. by studying the concentrations of syngas compositions (H\(_2\), CO, CO\(_2\) and CH\(_4\)) at two different temperatures (700°C and 900°C)[16]. Fig 2 shows the comparing results between experimental and simulated results. The simulation results are consistent with experimental tests, and the difference of syngas compositions between experimental and model data is within 3.5%, which can be accepted. The result indicates that the model can be used to provide accurate prediction of the process outputs.
3. Results and discussions

3.1. Influence of gasification temperature
Fig 3(a) shows the influence of gasification temperature on the compositions of syngas. As it shown, the H₂ and CO concentrations increased significantly when the temperature increases while CO₂ and H₂O concentrations decreased. On the other hand, the concentration of CH₄ decreases from 8.2% to 1.1% with temperature increasing.

![Figure 3](image_url)

Figure 3. (a) Effect of temperature of gasification on syngas composition, (b) Influence of temperature of gasification on CCE, LHV, HCE and FGC.

Fig 3(b) shows the influence of temperature of gasification on CCE, LHV, HCE and FGC of syngas, which indicates that the CCE, LHV, HCE and FGC of syngas are improved with temperature increasing, which meant a better gasification performance. In particular, with the temperature changing from 700 to 900 °C, the gasification efficiency shows a significant growth based on its rapid increasing in CO and H₂. The LHV exceed 5 MJ/m³ at 700°C, and a relatively small growth in syngas quality at the range from 900 to1000 °C. Simultaneously, the LHV and CCE value show a decreasing trend when gasification temperature increases to 900–1000°C. It can be seen that the appropriate gasification is around 900 °C.

3.2. Influence of air-fuel ratio
Fig 4(a) shows the influence of air-fuel ratio on syngas under 900°C. CO₂ concentration increased from 24% to 38.1% and CH₄ decreased from 14.2% to 6.7% when ratio of air-fuel increased from 0.1 to 1. H₂ concentration decreased from 18% to 12.4% with a rising air-fuel ratio, but CO concentration increased by 2.2%. Increasing in air-fuel ratio benefits the oxidization reactions (reactions R7–R11) but reduces the flammable gases content (CO, CH₄ and H₂).

![Figure 4](image_url)

Figure 4. (a) Influence of air-fuel ratio on syngas composition, (b) Influence of air-fuel ratio on CCE, LHV, HCE and FGC.
The influence of air-fuel ratio on the CCE, LHV, HCE and FGC is illustrated in Fig 4(b). The LHV, HCE, and FGC significantly decreased with the increase of air-fuel ratio. The decreasing of LHV and FGC is due to the enlarging dilution effect of nitrogen and the reducing components of combustible gas of H$_2$ and CH$_4$[17-18]. Meanwhile, the maximum CCE reached 46.0%, which was directly proportional to air-fuel ratio. A higher air-fuel ratio promotes oxidation reactions and reduces the amount of flammable gases. Thus, to maintain the LHV, HCE and FGC in the syngas, the amount of oxygen supplied needs to be in control. Considering process design, the appropriate air-fuel ratio for MSW oxygen gasification is around 0.4.

3.3. Influence of steam/MSW ratio

The influence of steam/MSW ratio on composition of syngas is illustrated in Fig 5(a). As it shows, the concentration of CO$_2$ decreased from 70.4% to 41.6% when the steam/MSW increased to 1.0 while the concentrations of CH$_4$ and CO were relatively decreased slightly. A higher steam/MSW ratio resulted in higher H$_2$O and H$_2$ content in the product steam[19-23]. The steam-methane reforming reactions (R4 and R5) are expected to promote CH$_4$ reacts with H$_2$O from steam and generate H$_2$, and this would cause CH$_4$ concentration decreased and H$_2$ content increased. Furthermore, contents of H$_2$, CO and CO$_2$ in the syngas are adjusted by steam injection through the combination of the Boudouard R1, the water-gas reaction R2 and shift reaction R3. By increasing the amount of steam, it shifts reaction R2 towards the positive direction, and reaction R1 towards the reverse direction, which contributes to H$_2$ concentration increased in a slight way and CO and CO$_2$ concentrations decreased.

![Figure 5](image_url)

*Figure 5. (a) Influence of steam/MSW ratio on syngas composition, (b) Influence of Steam/MSW ratio on CCE, LHV, HCE and FGC.*

The influence of steam/MSW ratio on CCE, LHV, HCE and FGC of syngas is depicted in Fig 5(b). The CCE increased steadily from 36.7% to 53.3 % while LHV increase significantly from 2 MJ/m$^3$ to 4.6 MJ/m$^3$ with the increase of steam/MSW ratio. The increase of flammable gases leads to the increase of LHV. Although more steam improves the quality of syngas and benefits the gasification performance of MSW, it is not beneficial to the temperature increase because of the heat consumption. Thus, the appropriate steam/MSW ratio for MSW oxygen gasification is around 0.4.

3.4. Process design approach

3.4.1. Fixed-bed chamber. According to the above discussion, a novel configuration of atmospheric fixed-bed chamber is proposed for pilot-scale gasification treatment process, which showed in Fig 6. The major system includes drying, pyrolysis, gasification and combustion. Meanwhile, a secondary combustion chamber is designed in order to guarantee the heat input of system.
As it knows, the most gas-solid reactions cannot reach the best homogenization temperature state in practical fixed-bed chamber. According to the above study results, the appropriate MSW gasification temperature includes drying (around 30–150°C), pyrolysis (around 150–450°C), gasification and combustion (around 700–900°C). Besides, the gasification chamber contains the gasification and oxidation process. The air-fuel ratio is maintained 0.4 by controlling the wind volume with auto-controlled air-valve. The steam produced by drying and MSW gasification, and the pyrolysis products all mixed gases enter the gasification chamber after separation and cooling. The secondary combustion chamber is designed in the outer layer of the gasification chamber and its temperature is expected to exceed 1000°C. The light hydrocarbons and flammable gases generated in the gasification section are introduced into the secondary combustion chamber for further combustion.

3.4.2. Auxiliary systems. The schematic of MSW treatment system is shown in Fig 7, which was consists of the fixed-bed chamber and the auxiliary systems. Auxiliary systems used for MSW gasification process consist of gas cooler/heater system, flue gas treatment system and recovery system. Gas cooler and heater system would decrease the temperature of the gases emitted from the secondary combustion chamber to 150°C and increase the temperature of the tar from the tar tank to 500°C by exchanging the heat. The measures taken to clean the gases emitted by the secondary combustion chamber include quenching, dedusting, adsorption and neutralization. For this purpose, a heat exchanger, boiler, duster, detarrer, scrubber, and stack are installed in series. The quenching can be seen in the gases cooler/heater system. Gas containing ash is purified by the duster, and collected in the tank. Some sawdust or straw adheres to the detarrer, as adsorbent to remove the tar of the gases. The scrubber is located at of the downstream of the detarrer, in which acidic gases are further purified. PH of scrubbing solution was controlled at 9.0 with sodium hydroxide. The main function of recovery system includes the tar and water recovery system. The tar with high temperature from the tar tank is injected into the chamber for secondary reaction. The cooling water provided from the water-tank is recycled to the boiler for the heat exchange, and the heated water can be used as hot spring or domestic hot water. The Sodium hydroxide was dissolved in water completely, and it goes back into the scrubber sprays to provide continuous recirculation.
Figure 7. Schematic of the MSW treatment system.

3.4.3. Feasibility Analysis. The following relation about energy balance should exist in MSW chamber treatment:

\[ Q_g + Q_a = Q_{st} + Q_r + Q_e + Q_{sl} + Q_f + Q_t \]  

(5)

Where the and \(Q_a\) represent the heat provided by the MSW and air respectively; the \(Q_{st}, Q_r, Q_{sl}, Q_f, Q_t\) are the heat discharged by steam, recycle of syngas, slag, gasifier and tar, respectively. The flow rate of MSW is 1 kg/hr; the steam in the syngas is from the moisture of MSW dried. The heat provided and discharged by the chamber is calculated by:

\[ Q_g = G_{\text{MSW}} \cdot LHV_{\text{MSW}} \]  

(6)

\[ Q_s = G_{\text{steam}} \cdot H_{S} \]  

(7)

\[ G_{\text{steam}} = G_{\text{MSW}} \cdot MC \]  

(8)

\[ Q_r = G_r \cdot LHV_r \]  

(9)

\[ G_r = G_{\text{MSW}} \cdot CGE \cdot FGC \]  

(10)

\[ Q_t = C_i \cdot M_i \cdot \Delta t \]  

(11)

The \(G_{\text{MSW}}, G_{\text{steam}}, G_{\text{tar}}, G_r\) denote the weight of MSW, steam, tar, recycle of syngas, respectively; the \(Q_{\text{st}}, C_i, M_i\) and \(\Delta t\) represent the heat lose, the particular heat capacity, the weight of substance \(i\), and the temperature changes.

Table 4 shows the heat balance of pyrolysis and gasification process. With the recovery system, the steam, tar, and flammable gases recycle to the gasification system, which can obtain additional 4402.57 kJ/kg of heat. The heat efficiency of fixed-bed chamber can increase significantly without adding any auxiliary fuel to the gasification system, which means the heat of chamber system can realize self-sufficiency.

| Contents       | Heat supply | Heat discharge |
|----------------|-------------|----------------|
|                | MSW | Air | Steam | Recycle of syngas | Exhaust | Slag | Gasifier | Tar |
| Unit Value (kJ/kg) |     |     |       |       |         |       |         |     |
|                | \(Q_g\) | \(Q_a\) | \(Q_s\) | \(Q_{st}\) | \(Q_r\) | \(Q_e\) | \(Q_{sl}\) | \(Q_f\) | \(Q_t\) |
| Sum(kJ/kg)     | 4951.2 | 12.87 | 1587.5 | 1444 | 28.8 | 150 | 382.7 | 1371.07 |

4. Conclusion

The simulation is developed with RYield, RStoic and RGibbs modules in Aspen plus. The simulation results are consistent with experimental tests, and the difference of syngas compositions between experimental and model data is within 3.5%, which is feasible and valuable for practical usage. To maintain the LHV, HCE and FGC in the syngas and consider the process design, the appropriate
gasification temperature is around 900°C, while the appropriate air-fuel and steam/MSW ratio for MSW gasification is around 0.4 and 0.4 respectively. A novel configuration of atmospheric fixed-bed chamber is proposed for pilot-scale gasification treatment process. The heat efficiency of fixed-bed chamber can increase significantly as a result of heat recovery system, and the heat of chamber system can realize self-sufficiency.

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References
[1] He J, Zhang H, Lv F and Shao LM. (2015) Treatment of Household Waste in Small Towns of China: Status, Basic Conditions and Appropriate Modes. Journal of Agricultural Resources and Environment, 2: 116-120.
[2] He M, Hu Z, Xiao B, Li J, Guo X, Luo S, et al. (2009) Hydrogen-rich gas from catalytic steam gasification of municipal solid waste (MSW): Influence of catalyst and temperature on yield and product composition. International Journal of Hydrogen Energy, 34(1): 195-203.
[3] Niu M M, Huang Y J, Jin BS, Wang X Y. (2013) Simulation of Syngas Production from Municipal Solid Waste Gasification in a Bubbling Fluidized Bed Using Aspen Plus. Industrial & Engineering Chemistry Research, 52(42): 14768-14775.
[4] Doherty W, Reynolds A and Kennedy D. (2009) The effect of air preheating in a biomass CFB gasifier using Aspen Plus simulation. Biomass & Bioenergy, 33(9): 1158-1167.
[5] Chen C, Jin Y Q, Yan J H and Chi Y. (2013) Simulation of municipal solid waste gasification in two different types of fixed bed reactors. Fuel, 103(1): 58-63.
[6] Ramzan N, Ashraf A, Naveed S, Malik A. (2011) Simulation of hybrid biomass gasification using Aspen plus: a comparative performance analysis for food, municipal solid and poultry waste. Biomass & Bioenergy, 2011, 35(9): 3962-3969.
[7] Chen C, Jin Y Q, Yan J H and Chi Y. (2010) Simulation of municipal solid waste gasification for syngas production in fixed bed reactors. Journal of Zhejiang University (English Edition) (Series A: Applied Physics & Engineering), 11(8): 619-628.
[8] Begum S, Rasul M G and Akbar D. (2014) A Numerical Investigation of Municipal Solid Waste Gasification Using Aspen Plus simulation. Procedia Engineering, 90: 710-717.
[9] Begum S, Rasul MG, Akbar D, Ramzan N. (2013) Performance analysis of an integrated fixed bed gasifier model for different biomass feedstocks. Energies, 6(12): 6508-6524.
[10] He C, Feng X, Kim H C, Li A X, Liu J Y. (2014) Industrial-scale fixed-bed coal gasification: modeling, simulation and thermodynamic analysis. Chinese Journal of Chemical Engineering, 05: 522-530.
[11] Peters J F, Banks S W, Bridgewater A V, Dufour J. (2017) A kinetic reaction model for biomass pyrolysis processes in Aspen Plus. Applied Energy, 188: 595-603.
[12] Emun F, Gadalla M, Majozi T, Boer D. (2010) Integrated gasification combined cycle (IGCC) process simulation and optimization. Computers & Chemical Engineering, 34(3): 331-338.
[13] Lai Z Y, Ma X Q, Tang Y T, Lin H. (2011) A study on municipal solid waste (MSW) combustion in N/O and CO/O atmosphere from the perspective of TGA. Energy, 36(2): 819-824.
[14] Skoulou V, Zabaniotou A, Stavropoulos G, Sakelaropoulos G. (2008) Syngas production from olive tree cuttings and olive kernels in a downdraft fixed-bed gasifier. International Journal of Hydrogen Energy, 33(4): 1185-1194.
[15] Palma C F, Martin A D. (2013) Model based evaluation of six energy integration schemes applied to a small-scale gasification process for power generation. Biomass & Bioenergy, 54(4): 201-210.
[16] Arena U. (2012) Process and technological aspects of municipal solid waste gasification. A review. Waste Management, 32(4): 625-632.

[17] Niu M M, Huang Y J, Jin B S, Wang X Y. (2014) Oxygen Gasification of Municipal Solid Waste in a Fixed-bed Gasifier. Chinese Journal of Chemical Engineering (English Edition), 22(9): 1021-1026.

[18] Atnaw SM, Sulaiman SA, Yusup S. (2011) A simulation study of downdraft gasification of oil-palm fronds using ASPEN PLUS. Journal of Applied Sciences, 11(11): 1913-1920.

[19] Yuan S, Zhou Z J, Li J, Wang F C. (2012) Nitrogen conversion during rapid pyrolysis of coal and petroleum coke in a high-frequency furnace. Applied Energy, 92: 854-859.

[20] Wei L, Xu S, Zhang L, Liu C, Zhu H, Liu S. (2007) Steam gasification of biomass for hydrogen-rich gas in a free-fall reactor. International Journal of Hydrogen Energy, 32(1): 24-31.

[21] Li E P, Chen H Y, Shang Y Y, Pan J, Hu Q. (2017) Research and demonstration results for a new "Double-Solution" technology for municipal solid waste treatment. Waste Management, 69: 558-566

[22] Deng N. (2019) Simulation analysis of municipal solid waste pyrolysis and gasification based on Aspen plus. Frontiers in Energy, 13(1):64-70.

[23] Zhao K, Ren Y J. (2010) Analysis and countermeasure of thermal efficiency of cracking furnace. Ethylene Industry, 22(2): 46-51.