# Experimental study on the controlled air oxidation of sawdust in a packed-bed reactor

**Meng Qingmin, Chen Xiaoping**[†]**, Bu Changsheng, and Ma Jiliang**

School of Energy and Environment, Southeast University, Nanjing 210096, China
(*Received 8 December 2010 • accepted 3 August 2011*)

**Abstract**–The controlled air oxidation technology is a promising way of disposing medical waste, which has been a huge challenge in China. It converts waste through partial oxidation into a gaseous mixture, small quantities of char and condensable compounds. But operational performance of the primary chamber of the controlled air incinerator is poorly understood, leading to difficulty in control. In this paper, a packed-bed reactor was established to study the effect of $O_2$ concentration on sawdust oxidation. The feed gas flow rate was kept constant at $0.6 \, m^3/h$ at room temperature (26 °C) with $O_2$ concentrations varied from 6% to 12%. Temperature profiles of the beds, product yields and gas compositions in the out-of-bed fuel gas were measured in detail. The results showed that the sawdust beds achieved low temperatures for the given $O_2$ concentrations and leveled off in the oxidation processes. The bed temperatures increased and the solid yields decreased with the increase of $O_2$ concentrations. When the $O_2$ concentration was 10%, the gas yield reached a minimum and the liquid reached a maximum correspondingly. When the $O_2$ concentration increased from 6% to 10%, the peak concentrations of CO and $CH_4$ in the gas yield increased. However, when the $O_2$ concentration exceeded 10%, CO and $CH_4$ concentrations decreased. As $O_2$ concentration varied from 6% to 12%, $CO_2$ concentration increased continuously. This study provides a fundamental insight that the reaction processes could be well regulated by means of adjusting the feed air in practical units.

Key words: Sawdust, Controlled Air Oxidation, Packed-bed

## INTRODUCTION

Medical waste includes materials produced in the course of health protection, medical treatment and scientic research. It forms a separate category-medical or health care waste [1] and constitutes a large part of the hazardous wastes. Many countries have started to pay more attention to generation and management of medical waste [2-11]. Hazardous waste pollution controlling is also a huge challenge to Chinese environmental management. At present, the production volume is around one million tons per year and increases at a rate of about 3-6%. Most of the medical waste is improperly treated in poorly designed or inadequately operated incinerators [2], producing a signicant quantity of hazardous pollutants, such as dioxins, HCl, and heavy metals including Cd, Hg, and Pb.

In recent years, controlled air oxidation technology has emerged to address these issues and improves the energy output [12-18]. It converts waste through partial oxidation into a gaseous mixture, small quantities of char and condensable compounds. It is considered as one of the most efcient ways of converting waste into energy, and it is becoming one of the best alternatives for the reuse of solid waste.

The typical controlled air incinerator involves sequential thermochemical processes taking place in two separate chambers [19]. The primary combustion chamber accepts the waste feed in batches. The devolatilization of the waste is initiated under substoichiometric condition, which results in the production of CO and unburned hydrocarbons. Then, the products of partial combustion enter the secondary combustion chamber, resulting in the complete destruction of the volatile organic gases with excess air injection. The function of the primary combustion chamber is to decompose the waste with heat supplied partly by burning part of the waste. The devolatilization rate and the heat released in the primary combustion chamber primarily determine the combustion condition and the amount of auxiliary fuel required in the secondary combustion chamber.

Compared with waste combustion, substoichiometric conversion of these fuels into energy in packed beds has the benefit of lower bed temperature, largely preventing dioxins formation and reducing thermal $NO_X$ formation in the bed, lower dust carryover in the flue gases, simplified gas-treatment procedures and lower running costs [20-23].

A number of experiments and modeling work have been done in the past which have provided important information on waste combustion [24-27]. However, theories of controlled air oxidation technology are still immature, and the overall performance of controlled air incinerators was regulated by setting the temperature of the secondary chamber through auxiliary fuel. Operational performance of the primary chamber is not fully understood.

The objective of the present work is to study the effect of $O_2$ concentration on the oxidation performance of medical waste in a packed-bed reactor by using a contracted experimental facility. For convenience, wood was chosen as the oxidation sample. Results in terms of detailed characteristics such as temperature profiles, product yields and gas compositions are presented and discussed.

## EXPERIMENTAL SECTION

### 1. Materials Properties
A typical woody material, poplar sawdust, was used. The saw-

---

[†]To whom correspondence should be addressed.
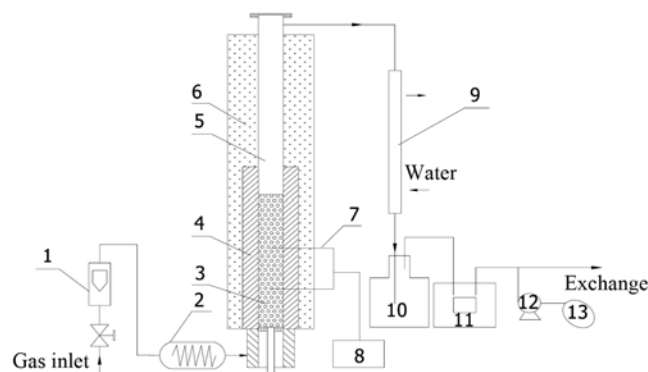E-mail: xpchen@seu.edu.cn

**Table 1. Proximate analysis, ultimate (dry basis) analysis and calorific value for sawdust**

| | Proximate analysis (wt%) | | | | Ultimate analysis (wt%) | | | | | Calorific value (MJ/kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Moisture | Volatile matter | Fixed carbon | Ash | C | H | O | N | S | |
| Sawdust | 13.81 | 74.19 | 11.06 | 0.54 | 47.73 | 5.73 | 38.07 | 1.03 | 0.21 | 17,109 |

**Table 2. Properties of the packed bed of sawdust**

| Mass (g) | Average bed height (mm) | Average bed density (kg/m$^3$) |
|---|---|---|
| 400 | 390 | 204 |



**Fig. 1. Schematic diagram of the experimental facility.**

| | |
|---|---|
| 1. Flowmeter | 8. Data acquisition |
| 2. Preheater | 9. Condenser |
| 3. Sawdust | 10. Scrubbing bottle |
| 4. Electric heater | 11. Gasometer |
| 5. Reactor | 12. Extraction pump |
| 6. Heat insulation cotton | 13. Bag |
| 7. Thermocouples | |

dust sample was screened with particle size about 1.5 mm. Proximate and ultimate analyses of the sawdust sample are presented in Table 1. The ultimate analysis results are similar to other experimental data in literature [28-31].

Besides the particle properties, the bed characteristics have an important impact on the heating rate, mass transport and residence time of volatiles. The main bed properties are shown in Table 2. The average bed density was measured by a precision balance and a graduated cylinder.

**2. Experimental Facilities and Procedures**

Fig. 1 shows the schematic diagram of the experimental facility. The main components of the facility include a gas feeding system, a gas pre-heater (3 kW) for heating the feed gas to a certain temperature, a packed-bed reactor, a bed heater (8 kW) for heating the reactor to the desired temperature, a condenser and a scrubbing bottle to cool and clean the gaseous stream, a data acquisition board linked with a PC. The reactor is made up of a stainless steel pipe which can withstand a high temperature about 1,200 °C. The height of the reactor is 1.2 m with the internal diameter of 80 mm. A bubble cap-type distributor was set at the bottom of reactor. Six caps were arranged in a circle with diameter of 56 mm uniformly. Four orifices with diameter of 2.5 mm were perforated on the top of each cap. The bed heater was installed around the reactor wall. A thick layer of

heat insulation cotton (Aluminum silicate) covered outside of the heater.

Before each experimental run, $N_2$ was introduced into the reactor to purge air for more than 10 minutes. In each experimental run, a feed gas mixture of $N_2$ and $O_2$ with a specified mixing proportion was preheated to 400 °C, and then supplied into the reactor through the gas distributor. At the same time, the bed heater was set to heat the reactor wall and maintained it at 400 °C.

The temperatures at the center of the reactor at positions of 100 and 200 mm above the gas distributor were measured by K-type thermocouples, which had been calibrated specially and recorded continuously by the data acquisition board. The product gas went sequentially through the condenser and scrubbing bottle to be cooled, removing the tar within it. The gas was sampled about every 5 minutes at the outlet of a gasometer and analyzed by gas chromatography. In the gas analyzer, only components of CO, $CO_2$, $CH_4$ and $O_2$ can be measured. Other gas components, including $N_2$ and other trace gases, cannot be measured.

At the end of each test, the bed heater was turned off, and the solid residues in the reactor and the liquids in the condenser were collected and weighed. The gas yield was calculated on the base of its measured volume and the gas components which were analyzed by gas chromatography. The mass balance for each test was calculated and the error was less than 4%.

During experiments, the feed gas flow rate was kept constant at 0.6 m$^3$/h at room temperature (26 °C). $O_2$ concentration was varied at 6%, 8%, 10% and 12%.

## RESULTS AND DISCUSSION

**1. Combustion and Controlled $O_2$ Oxidation Characteristics**

The conventional combustion of solid fuels is characterized by a series of successive temperature rises from room temperature to over 700 °C within a few minutes. Besides, complete combustion using excess air results in numerous disadvantages including production of large flue gas volumes, hazardous waste streams associated with the fly ash.

Conventional combustion means that fuels were completely combusted with high excess air coefficient. To compare with the performance of conventional combustion inside the packed-bed reactor, a combustion experiment was carried out in the same system at an air flow rate of 1.2 m$^3$/h. Fig. 2 shows the measured temperatures in the bed and compositions of the flue gas as functions of times. As can be seen in Fig. 2(a), the bed temperature at the height 100 mm reached 810 °C within 30 minutes, which was similar to that for other waste and biomass materials [15]. In Fig. 2(b), the $O_2$, $CH_4$, CO and $CO_2$ profiles show the typical behavior of sawdust combustion. All the $O_2$ was consumed by combustion in 26 minutes, leading to a rapid increase of $CO_2$. Besides, due to the excess air, production of large flue gas volumes brought many difficulties in
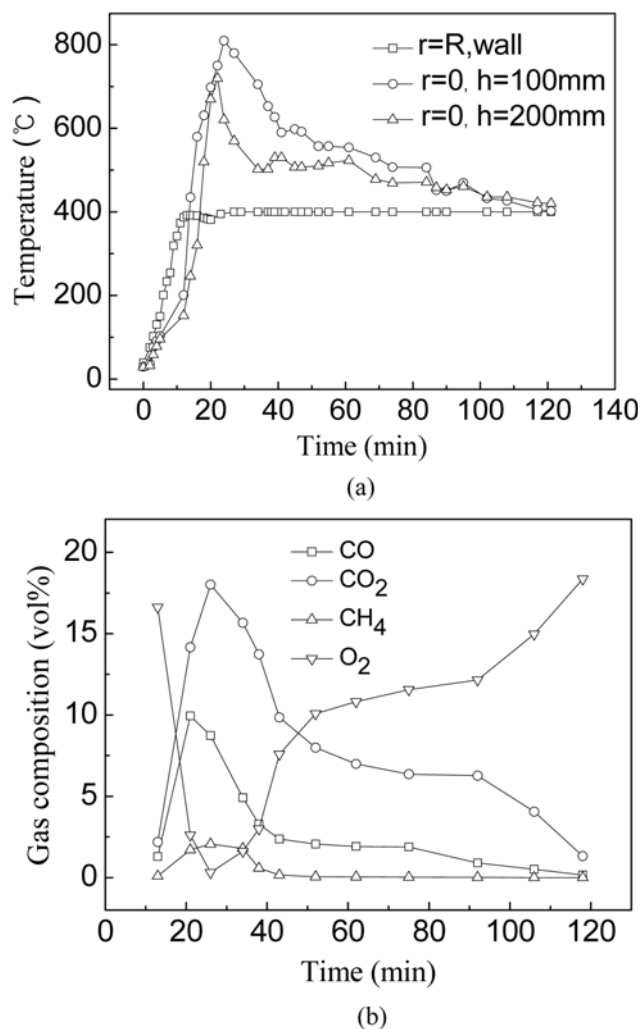
(a)



(b)

**Fig. 2. Temperatures (a) and gas compositions of the flue gas (b) in sawdust combustion at an air ow rate of 1.2 m³/h.**



(a)



(b)

**Fig. 3. Temperatures (a) and gas compositions of the flue gas (b) in sawdust oxidation at a mixed gas (6% $O_2$+94% $N_2$) flow rate of 0.6 m³/h.**

managing the flue gas.

While the objective of this paper is to study the controlled air oxidation, the waste is fired with less than the stoichiometric air requirement, usually from 40% to 60%. So a lower air flow rate was chosen. Fig. 3 shows the measured temperatures and gas compositions of the flue gas in sawdust oxidation for the feed gas flow rate of 0.6 m³/h. $O_2$ concentration in the feed gas mixture was 6% in volume. The whole oxidation process can be divided into three stages. At the beginning of the oxidation process, the sawdust was heated and the volatiles began to release. When the sawdust was heated to a certain temperature, an immediate oxidation reaction took place in the bed. As can be seen in Fig. 3(b), the concentrations of CO, $CO_2$ and $CH_4$ in the outgoing gas reached their maximum levels, and a rapid drop of the $O_2$ concentration was observed. Then, in the second stage, the gas compositions remained at low and stable levels for a relatively long time, which meant that a steady oxidation reaction took place. When concentrations of CO, $CO_2$ and $CH_4$ were almost zero and the $O_2$ concentration started to increase, it was considered the end of the devolatilization reaction. This was the beginning of the third stage. In industrial facilities, excess air would be injected into the chamber to combust the char completely.
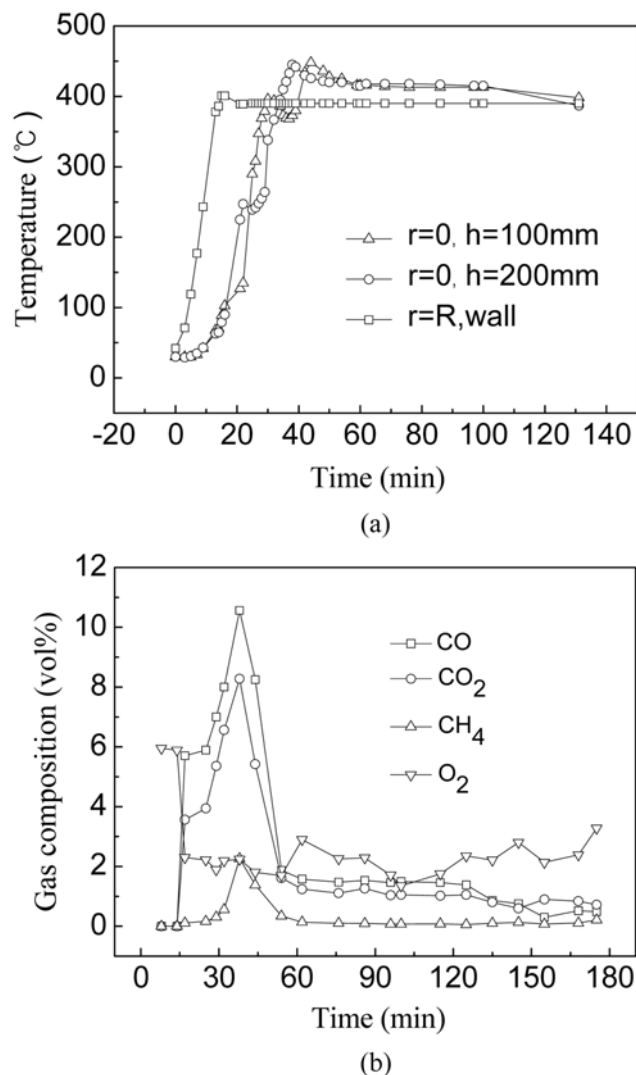
Compared with Fig. 2 for the combustion of sawdust, the peak temperature in the oxidation bed was much lower, only 445 °C at the bed height of 100 mm. Besides, the temperature at the height of 200 mm was in harmony with that in the position of 100 mm, which meant that the sawdust bed could maintain a steady state in the oxidation process. Nitrogen is a macronutrient for plants, critical to their growth, and in high concentration. Nitrogen, sulfur and chlorine are important in the formation of pollutants. The published research results indicated that $NO_X$ was emitted from the fuel bed simultaneously with the volatile matters during devolatilization when the temperature reached 600 °C [21] and was known to be sensitive to the equivalence ratio, producing high yields under air rich conditions [20]. Furthermore, high temperature led to the melt of heavy metal, which had a strong influence on ash disposal [20]. A lower bed temperature process led to lower $NO_X$ formation in the bed and produced available fuel gas which contained 10.56% CO and 2.26% $CH_4$. Therefore, due to the less feed gas, this technique combined a number of favorable properties, i.e., lower bed
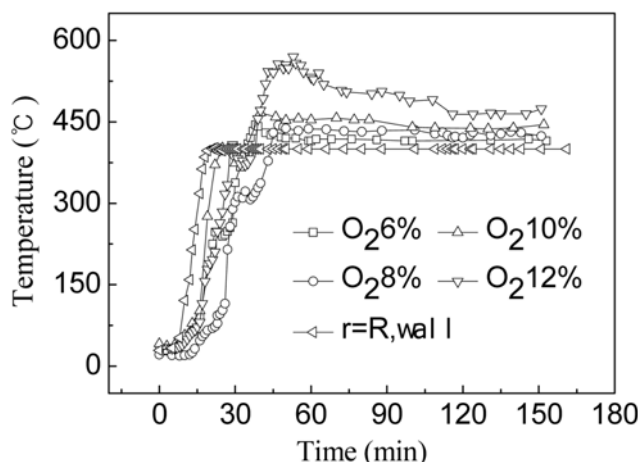
Fig. 4. Temperature profiles at different $O_2$ concentrations for bed height of 100 mm.



Fig. 5. Product yields vs. $O_2$ concentrations in feed gas.

temperature, largely preventing PCDD/Fs formation and reducing $NO_X$ formation in the bed, lower dust carryover in the flue gases, simplified gas-treatment procedures and lower running costs, which could be friendlier to environment.

## 2. Effect of $O_2$ Concentrations on Temperature Profiles

Temperature profiles in the bed were studied in order to obtain a better understanding of the oxidation process. Fig. 4 presents the temperature profiles at the bed height of 100 mm for the sawdust oxidation processes at different $O_2$ concentrations. Based on thermogravimetric results, wood decomposition took place after 220 °C [32-34]. Biomass degradation in a pure flow of $N_2$ is an endothermic process which requires external heat input. In contrast, gasification of wood is an exothermic process in theory. In this experiment, the heat for the temperature rise was provided by the heater, hot feed gas and the partial combustion which maintained the reaction. For all the performed experiments, the same thermal behavior was observed: the temperature rose to a certain point and then leveled off in the oxidation process. At the beginning of the run, the temperature of the reactor wall increased to the designed temperature with the rate about 15 °C/min. Due to the delay of the heat transfer, temperature rise of the sawdust had a lag. Then, because of the presence of $O_2$, oxidation reactions of pyrolysis products proceeded to provide the required heat for the successive thermal decomposition.

Temperature profiles also showed that the increase in $O_2$ concentration led to the increase in bed temperature. By changing the $O_2$ concentration from 6% to 12%, the temperature increased significantly. The bed temperatures for $O_2$ concentrations of 6%, 8%, 10% and 12% were 415 °C, 434 °C, 454 °C and 502 °C, respectively. For every 2% rise in $O_2$ concentration, temperature increased by about 20 °C. Hence, reaction processes could be well regulated by means of adjusting the feed air in practical equipment.

## 3. Product Yields

The oxidation products were divided into gas, liquid consisting of condensed vapor and tar, and solid residues including char and ash. Fig. 5 presents the product yields of sawdust for $O_2$ concentrations ranging from 6% to 12%. It can be observed that the increase in $O_2$ concentration led to the decrease in solid fraction. The maximum yield of residues (29.25 wt%) corresponded to the lowest $O_2$
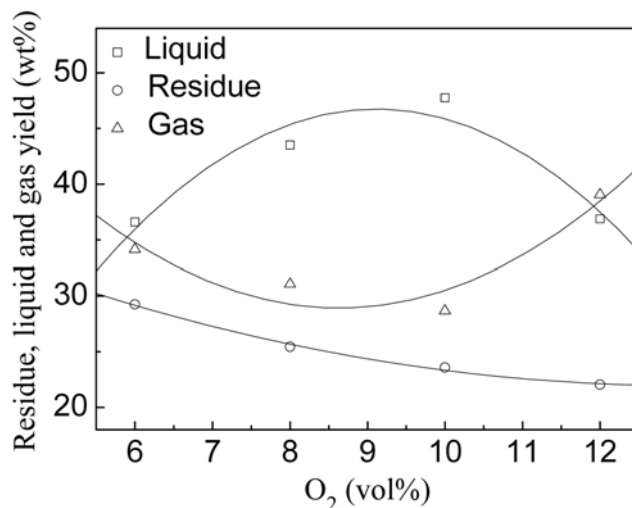
concentration. The yield of char decreased to 22.04 wt% at $O_2$ concentration of 12 vol%. This could be attributed to the high temperature caused by the richer amount of $O_2$ which led to more vigorous reaction. Therefore, high $O_2$ concentration led to low solid yield and high tar and gas yields.

Fig. 5 also shows that the gas yield reached a minimum at $O_2$ concentration of 10% while the liquid achieved a maximum correspondingly. This could be explained by the comprehensive effects of residence time of the volatile phase and the sawdust bed temperature. Generally, the longer the residence time of the volatile phase was, the better the cracking reaction of tar was [35]. As a result of low $O_2$ concentration, low temperature led to a low gas flow rate. Therefore, there would be enough time for tar cracking to generate gas. With the increase of $O_2$ concentration, which meant higher temperature in reactor and shorter residence time of the volatile phase, there would not be enough time for tar cracking to generate gas. Therefore, yields of tar increased and yields of gas decreased as $O_2$ concentrations varied from 6% to 10%. However, it can be observed that yields of tar decreased and yields of gas increased as $O_2$ concentration from 10% to 12%. This suggests that there was a critical point, at which the gas formation not only depended on the residence time but also was affected by the sawdust bed temperature. When $O_2$ concentration was 12%, the temperature was high enough to cover up the influence of the residence time.

## 4. Gaseous Compositions

The compounds analyzed in the gas product were CO, $CO_2$, $CH_4$ and $O_2$. Fig. 6 displays the volume percentage of each compound in the gas product as a function of times with $O_2$ concentrations ranging from 6% to 12%.

When the feed $O_2$ concentration was 6%, the maximum concentrations of CO, $CO_2$ and $CH_4$ were 10.56, 8.28 and 2.24 (vol%), respectively. On the other hand, these maximum values increased slightly with the increase of $O_2$ concentrations. For the cases that the $O_2$ concentrations in the feed gas equaled to 6, 8, 10 and 12 (vol%), the corresponding peak CO concentrations during the oxidation were 10.56, 11.42, 12.81 and 11.98, respectively, while the peak values for $CO_2$ were 8.28, 11.88, 13.81 and 14.27 (vol%), respectively. And in the case of $CH_4$, the increase was slight as the $O_2$ concen-
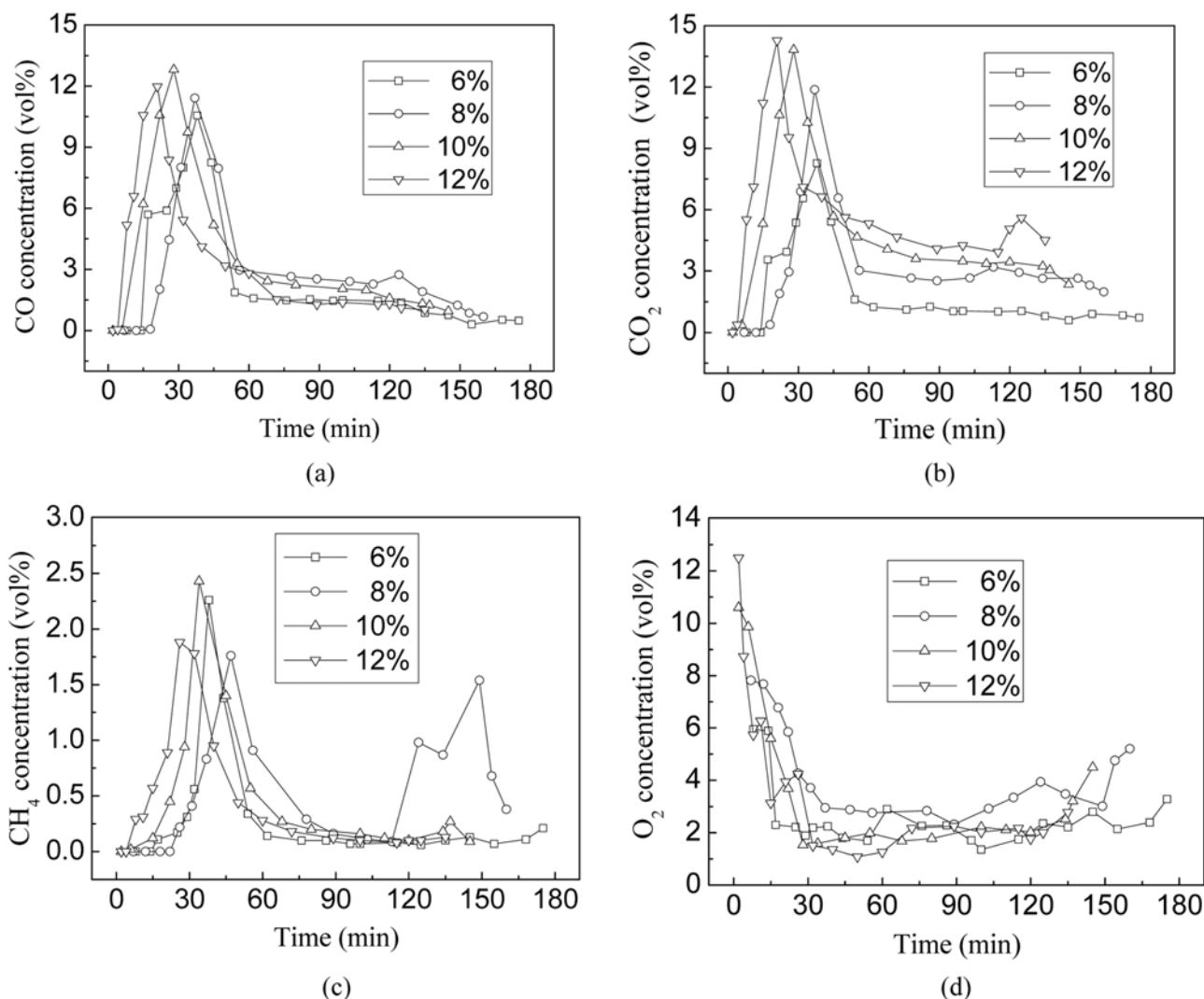
**Fig. 6. Evolution of gas compositions vs. time with $O_2$ concentrations ranging from 6% to 12%.**

tration increased. The conclusion can be drawn that the peak concentration of CO, $CH_4$ and $CO_2$ increased when the $O_2$ concentration increased from 6% to 10%. This was mainly because reaction degree at higher $O_2$ concentration was deeper than that at lower $O_2$ concentration. Furthermore, when higher $O_2$ concentration was used, less $N_2$ was poured to the reactor and therefore the product gas was less diluted. However, when the $O_2$ concentration reached 12%, CO concentration decreased slightly and the increase of $CO_2$ concentration was comparatively large. The possible reason for this behavior was that more CO converted into $CO_2$ at higher $O_2$ concentrations.

## CONCLUSIONS

A packed-bed reactor was established to study the effect of $O_2$ concentration on sawdust oxidation.

(a) The sawdust beds achieved low temperatures for given $O_2$ concentrations and leveled off in the oxidation processes. Reaction processes could be well regulated by means of adjusting the feed air in practical equipment.

(b) For all the performed experiments, the same thermal behav-

ior was observed. The bed temperature rose to a certain point and then maintained almost steady in the oxidation process. Increased $O_2$ concentration led to the increase in bed temperature. Temperature increased by about 20 °C for every rise 2% in $O_2$ concentration. The bed temperatures for $O_2$ concentrations of 6%, 8%, 10% and 12% were 415 °C, 434 °C, 454 °C and 502 °C, respectively.

(c) Increased $O_2$ concentration led to the decrease in solid fraction, the gas yield reached a minimum at about 10%, and the liquid achieved a maximum in correspondence. Then, there was a critical point where could be observed that yields of tar decreased and yields of gas increased when $O_2$ concentrations varied from 10% to 12%.

(d) The peak concentrations of CO, $CH_4$ and $CO_2$ increased when the $O_2$ concentration increased from 6% to 10%. When the $O_2$ concentration reached 12%, CO concentration decreased and $CO_2$ concentration increased slightly.

## REFERENCES

1. P. S. Li, L. S. Sun, J. Xiang and Y. H. Xiong, China Environmental Science Press, Beijing (2006).

2. H. Duan, Q. Huang, Q. Wang, B. Zhou and J. Li, *J. Hazard. Mater.*, **158**, 221 (2008).
3. Sabihajavied, M. Tufail and S. Khalid, *Microchem. J.*, **90**, 77 (2008).
4. Y. Jang, C. Lee, O. Yoon and H. Kim, *J. Environ. Manage.*, **80**, 107 (2006).
5. J. Blenkharn, *Waste Manage.*, **26**, 315 (2006).
6. A. Bdour, B. Altrabsheh, N. Hadadin and M. Alshareif, *Waste Manage.*, **27**, 746 (2007).
7. N. Marinkovic, K. Vitale, N. Holcer, A. Dzakula and T. Pavic, *Waste Manage.*, **28**, 1049 (2008).
8. A. Woolridge, P. Phillips and A. Denman, *Resour. Conserv. Recycl.*, **52**, 1198 (2008).
9. D. Rogers and A. Brent, *Waste Manage.*, **26**, 1229 (2006).
10. M. Matsui, A. M. Ziad, Riyadh and S. Arabia, *Chemosphere*, **53**, 971 (2003).
11. M.Almuneef, A. M. Ziad, Riyadh and S. Arabia, *Am. J. Infection Control*, **31**, 188 (2003).
12. Z. A. Zainal, A. Rifau, G. A. Quadir and K. N. Seetharamu, *Biomass Bioenergy*, **23**, 283 (2002).
13. S. C. Bhattacharya, A. H. M. Mizanur Rahman Siddique and H.-L. Pham, *Energy*, **24**, 285 (1999).
14. S. Luo, B. Xiao, X. Guo, Z. Hu, S. Liu and M. He, *Int. J. Hydrog. Energy*, **34**, 1260 (2009).
15. Y. Cao, Y. Wang, J. Riley and W. Pan, *Fuel Process. Technol.*, **87**, 343 (2006).
16. X. Guo, B. Xiao, S. Liu, Z. Hu, S. Luo and M. He, *Int. J. Hydrog. Energy*, **34**, 1265 (2009).
17. S. Luo, B. Xiao, Z. Hu, S. Liu, Y. Guan and L. Cai, *Bioresour. Technol.*, **101**, 6517 (2010).
18. C. G. Wang, L. L. Ma, Y. Gao and C. Z. Wu, *Korean J. Chem. Eng.*, **25**, 738 (2008).
19. W. Jangsawang, B. Fungtammasan and S. Kerdsuwan, *Energy Convers. Manage.*, **46**, 3137 (2005).
20. B. M. Jenkins, L. L. Baxter and T. R. Miles, *Fuel Process. Technol.*, **54**, 17 (1998).
21. L. Liang, R. Sun, J. Fei, S. Wu, X. Liu, K. Dai and N. Yao, *Bioresour. Technol.*, **99**, 7238 (2008).
22. Y. B. Yang, V. N. Sharifi and J. Swithenbank, *AIChE J.*, **52**, 809 (2006).
23. T. Malkow, *Waste Manage.*, **24**, 53 (2004).
24. W. Yang, A. Ponzio, C. Lucas and W. Blasiak, *Fuel Process. Technol.*, **87**, 235 (2006).
25. H. Thunman and B. Leckner, *Proc. Combust. Inst.*, **30**, 2939 (2005).
26. P.-A. Maria, J. C. Bruno and A. Coronas, *Renewable Sustainable Energy Rev.*, **03**, 1 (2010).
27. P. Baggio, M. Baratieri, L. Fiori, M. Grigiante, D. Avi and P. Tosi, *Energy Convers. Manage.*, **50**, 1426 (2009).
28. Y. Yang, C. Ryu, A. Khor, V. Sharifi and J. Swithenbank, *Fuel*, **84**, 2026 (2005).
29. J. J. Hernández, G. Aranda-Almansa and A. Bula, *Fuel Process. Technol.*, **91**, 681 (2010).
30. K. S. Francesco Miccio, J.-P. Schosger and D. Baxter, *Korean J. Chem. Eng.*, **25**, 721 (2008).
31. L. M. C. Prompubess, P. Piumsomboon and P. Kuchontara, *Korean J. Chem. Eng.*, **24**, 989 (2007).
32. B. Benkoussas, J.-L. Consalvi, B. Porterie, N. Sardoy and J.-L. Loraud, *Int. J. Therm. Sci.*, **46**, 319 (2007).
33. C. K. J. Chattopadhyay, R. Kim and D. Pak, *Korean J. Chem. Eng.*, **25**, 1047 (2008).
34. J. Supunnee, T. Chaiyot and T. Malee, *Korean J. Chem. Eng.*, **27**, 791 (2010).
35. G. Chen, J. Andries, Z. Luo and H. Spliethoff, *Energy Convers. Manage.*, **44**, 1875 (2003).