



Article

Simulated biomass tar removal mechanism by a Quench Coupled with Adsorption Technology (QCADT)☆

Xiaosong Zhang^{1,2}, Jiawei Pan^{1,2}, Liang Wang³, Hongqi Sun⁴, Yuezhao Zhu^{1,2}, Haijun Chen^{1,2,*}¹ Jiangsu Key Laboratory of Process Enhancement and New Energy Equipment Technology, Jiangsu Engineering Laboratory of Energy Conservation and Environmental Protection Technologies and Equipment in Process Industry, Nanjing 211816, China² School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China³ College of Chemistry and Chemical Engineering, Nanjing Tech University, Nanjing 210009, China⁴ School of Engineering, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA6027, Australia

ARTICLE INFO

Article history:

Received 24 March 2019

Received in revised form 5 June 2019

Accepted 16 June 2019

Available online 15 July 2019

Keywords:

Biomass gasification

Tar removal

Adsorption

Couple

Pore

ABSTRACT

Tar removal is a bottleneck in the smooth commercialization of biomass gasification technology. Based on introducing adsorption process into Quench Coupled with Adsorption Technology (QCABT) previously proposed by the author's group, Quench Coupled with Adsorption Technology (QCADT) has been developed to narrow this gap. Additionally, benzene and naphthalene, which are more similar to the real tar for containing aromatic ring structures, were adopted as light and heavy simulated tar, respectively. Also their removal behavior by QCADT was investigated. The results show that the removal mechanism of QCADT is similar to that of QCABT, except for the higher overall tar removal rate due to adsorption effect. Adsorbents with both micro- and narrow mesopores exhibit a better benzene removal performance, while narrow mesopores play dominant roles in naphthalene removal. Penetration adsorption loading of benzene and naphthalene on AC-1 can reach $0.38 \text{ g} \cdot \text{g}^{-1}$ and $0.34 \text{ g} \cdot \text{g}^{-1}$, respectively. The sawdust hardly has any tar removal effect. Combined micro- and meso-pores, will benefit both deep tar removal and large adsorption rate, providing a high tar removal efficiency. © 2019 The Chemical Industry and Engineering Society of China, and Chemical Industry Press Co., Ltd.

All rights reserved.

1. Introduction

The biomass gasification process is inevitably accompanied by tar ($0.5\text{--}100 \text{ g} \cdot \text{m}^{-3}$), which normally condenses at reduced temperature and causes blocking and fouling of engines at that temperature. Tar also plays a significant (negative) role in wastewater management, as in most traditional water scrubber tars and condensed water are mixed, producing costly and challenging water treatment problem. Removal of tars from the process wastewater requires considerable investments that can even be dramatic as some tar components show poisoning behaviour in biologic wastewater treatment systems (e.g., phenol). The tar problem is one of the major obstacles to the smooth industrialization of biomass gasification processes [1,2]. So far, the tar problem has not been effectively resolved.

The recovery method adopts the concept of physical separation unit operation such as absorption or rectification, to capture of Volatile Organic Compounds (VOCs) [3,4]. Much attention has been paid to the

recovery and removal of gas in the trace of organic matter, due to its designability on a molecular level without consideration of VOC origin [5,6].

The oil-based absorption method for tar recovery and removal has achieved small-scale commercial applications [7,8]. Research at the Energy Center of the Netherland (ECN) has firstly developed Oil-based Gas washer (OLGA) process, which is based on a multiple stage scrubber, using special scrubbing oils instead of water. The total tar content was reduced by 99%, and tar dew point decreased from higher than 250°C to 5°C . Besides, ECN has further developed the OLGA technology together with Dahlman Industrial Group. The engineering for OLGA pilot had been finished, and it was launched to the market by Dahlman since 2007 [9].

To lower operation prices of OLGA relative method further, the author's group has developed Quench Coupled with Adsorption Technology (QCABT) [6], in which, a quench unit was specially designed to condensate heavy tar. QCABT exhibits both cooling and absorption effects in the quench scrubber upon the removal of cyclohexane (simulated heavy tar), providing a total removal efficiency of 98%.

Adsorbents are attractive for tars with different rings, due to their high designable porosity and surface [3]. Therefore, among various physical techniques, adsorption is considered as a better process for tar removal compared to other methods because of deep removal, convenience, smooth operation, and simplicity of design [3,10].

☆ Supported by the Six Talent Peaks Project in Jiangsu Province (2015-ZBZ-015), the top-notch academic programs project of Jiangsu Higher Education Institutions (PPZY2015A022) and the National Key Research and Development Program of China (2018YFB1502900, 2018YFB1502903).

* Corresponding author at: School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China.

E-mail address: chenhj@njtech.edu.cn (H. Chen).

Table 1
Main raw materials and reagents

Name	Specification	Manufacturer
Benzene Naphthalene	A.R.	Shanghai Ling Feng Chemical Reagent Co., Ltd.
AC-1	Coconut shell based activated carbon	Mulinsen Activated Carbon Group
AC-2	Wood-based activated carbon	
Sawdust	16–24 mesh, pine chips based	Self-prepared

Anchan *et al.* [11], Phuphuakrat *et al.* [12], Tarnpradab *et al.* [13], and Paethanom *et al.* [14] have introduced an adsorption process for tar removal, through combination with other decomposition or absorption units. They carried out successful research on oil scrubbers and char adsorption for tar removal. The lab scale experimentation demonstrated that for $0.045 \text{ m}^3 \cdot \text{h}^{-1}$ pyrogas, the 1 L oil scrubber was combined with a 41 g char adsorption bed and 97.6% gravimetric tar removal efficiency was obtained. For pilot-scale, pyrogas was sampled at $0.7 \text{ m}^3 \cdot \text{h}^{-1}$, consisting of a 15 L oil scrubber combined with a 922 g char adsorption bed. The test was successfully accomplished with 98.7% gravimetric tar removal. The downstream engine ran smoothly, and the electric load was constant [15]. However, in this above-mentioned process, it might suffer the crisis of tar plugging problems in the oil scrubber due to a temperature of lower than 50°C .

Besides, it has been reported that activated carbon or char performs as an effective adsorbent due to its high porosity property [16,17]. Also, biochars are the by-products of biomass pyrolysis/gasification which could be simply gasified to recover the energy without frequent regeneration. Tar elimination by efficient adsorption and catalytic conversion by carbon-based adsorbents/catalysts might be attractive.

Although adsorption process shows potential for deep tar removal, the mechanism, selectivity, and stability of adsorbents for tar still need to be further improved.

To overcome the limits on existing tar removal based on recovery philosophy, with adsorption replacing absorption in QCABT, a Quench Coupled with Adsorption Technology (QCADT) was developed and patented by the author's group [18,19]. A preliminary test shows that the tar has been removed cascaded under the idea of QCADT, providing a residual tar concentration of less than $10 \text{ mg} \cdot \text{m}^{-3}$, which is distinctly lower

than that of OLGA [19]. This previous work focuses mainly on tar removal effects, while it lacks deep insights into the coupling tar removal mechanism of the tar molecular size and the pore size of the adsorbent.

In this paper, naphthalene (heavy tar) and benzene (light tar) were selected as simulated tar, respectively. The relationship between tar removal and adsorbent pore structure is analyzed. The competitive adsorption behavior of light and heavy tar is investigated. Mechanism of the staged removal of simulated tar by the QCADT is explored, providing a fundamental basis for deep removal of tar from biomass producer gas.

2. Materials and Methods

2.1. Main materials and reagents

The primary raw materials and reagents are shown in Table 1. Sawdust is a self-prepared pine chip with a mesh of 16 to 24 and a water content of 9.6%.

2.2. Experimental section

Based on QCABT, QCADT mainly contains a quench scrubber and an absorber. The quench scrubber is a spray tower, in which the biomass producer gas is cleaned by heavy tar itself. The heavy tar will be condensed upon the quench scrubber, after being separated from the fine solids, as is recycled as the scrubbing oil, or directly as the product. In the next stage (the adsorber/stripper), lighter gaseous tars are absorbed by the adsorbent, which results in a product gas practically free from tars and solids. In the adsorbent column, the adsorbent is saturated by these lighter tars. This saturated adsorbent is regenerated if the hot air or water steam is used to strip the tars.

The QCADT experimental device illustrated in Figs. 1 and 2 was modified from previously established QCABT testing rig, by using an adsorber of $\phi 6 \text{ nm} \times 1 \text{ nm} \times 150 \text{ mm}$ replacing the former absorber. All of the devices were made of stainless steel for larger temperature tolerance. The testing process of QCADT can reference to that of QCABT.

For pure naphthalene adsorption, a sampling pump can't take effect. A fixed mass of naphthalene was put into the quench scrubber. Tar vapor was then transferred into the quench scrubber by a nitrogen carrier gas maintained at $100 \text{ ml} \cdot \text{min}^{-1}$ using a mass flowmeter (S49 32/MT, Beijing Kuchang Horiba Metron Precision Instrument Co. Ltd.), and the heavy tar formed a condensate. For other processes, tar mixture was delivered into

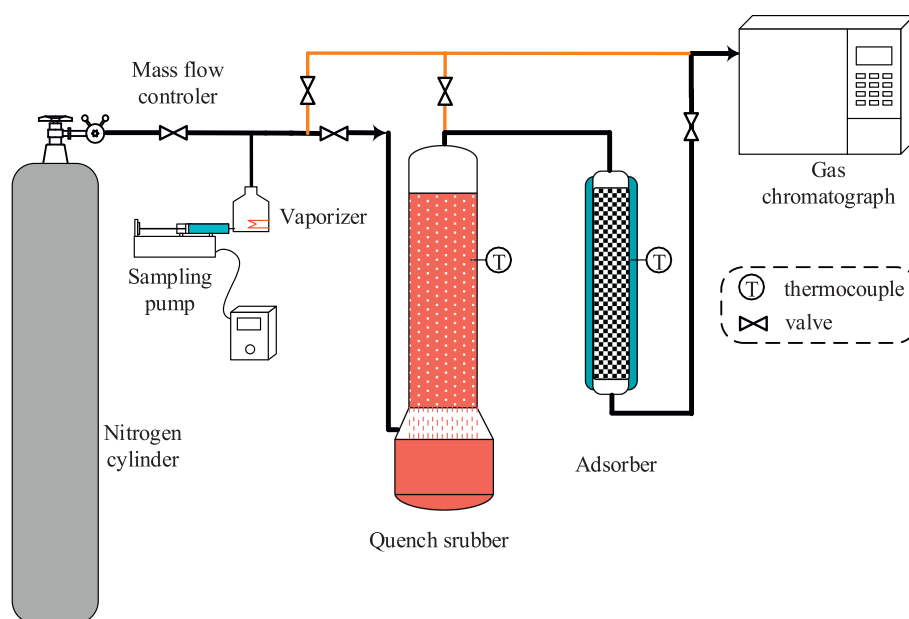


Fig. 1. Schematic diagram for the QCADT tar removal test rig.

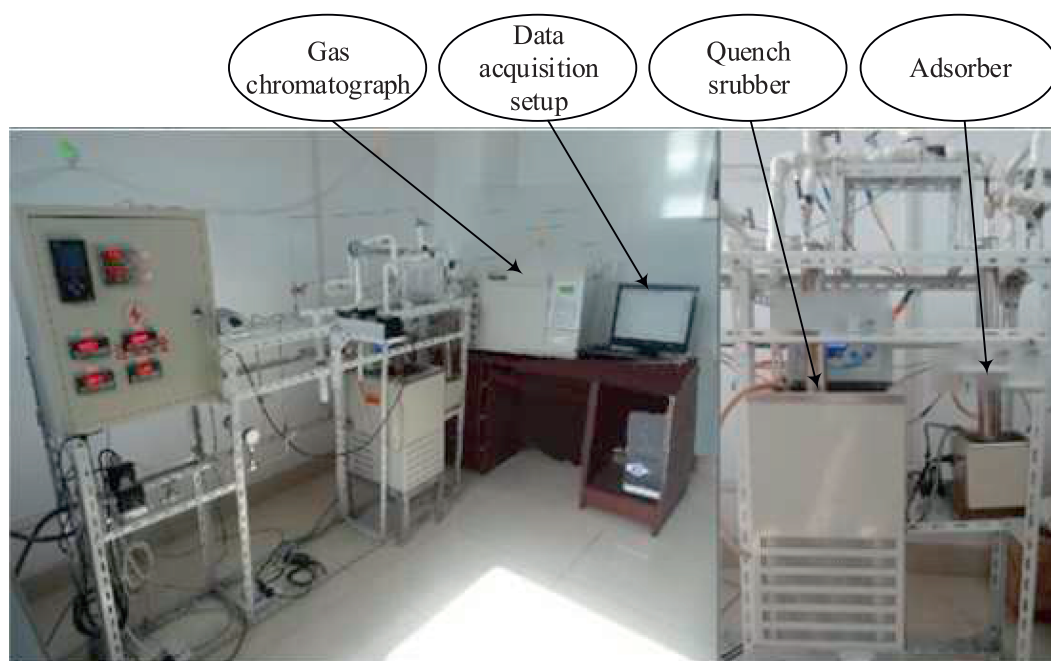


Fig. 2. Photo of the QCADT test rig.

the vaporizer at 200 °C by the sampling pump (TJ-3A, Baoding Longer Pump Co. Ltd.) followed by the quench scrubber. The sampling of tar was conducted by an online chromatograph (SP6890, Rainbow Chemical Instrument Co. Ltd., Shandong Lunan) at the entrance and exit of the quench scrubber, and at the exit of the adsorber, respectively. The sampling method is generally similar to that of reference [6], except for a column temperature of 200 °C due to the presence of naphthalene.

In the tar removal process, simulated tar samples were maintained at a concentration of 150–300 g·m⁻³, which is a typical tar content in fuel gas just outside of the gasifier. The sampling concentration was 90 wt%–95 wt% for the simulated light tar, benzene. The quench scrubber and the adsorber temperatures were controlled at 50 °C and in the ranges 40–60 °C, respectively. In addition, the adsorbent was 0.5 g in the adsorber.

The penetration of the tar and the equilibrium adsorption capacity are determined by the adsorption penetration curve, which can be calculated as follows:

$$q = \frac{F \times C_0 \times 10^{-9}}{W} \left[t_s - \int_0^{t_s} \frac{C_i}{C_0} dt \right]$$

where:

q	Penetration or equilibrium adsorption capacity, g·g ⁻¹
F	Simulated gas volume flow rate, ml·min ⁻¹
C_i	Outlet concentration of benzene or naphthalene, mg·m ⁻³
C_0	Inlet concentration of benzene or naphthalene, mg·m ⁻³
W	Adsorbent mass, g
t	Adsorption time, min
t_s	Adsorption saturation time, min

Table 2
Porosities of the adsorbents

Name	S_{BET} (m ² ·g ⁻¹)	Iodine value (mg·g ⁻¹)	Average pore diameter (nm)		Pore volume (cm ³ ·g ⁻¹)
			Micropore	Mesopore	
AC-1	1486.80	1450	0.54	2.06	0.3616
AC-2	805.62	–	–	3.38	0.1572
Sawdust	16.30	–	–	13.11	0.0032

2.3. Specific surface area measurement

The specific surface area (S_{BET}) and pore structure of the adsorbent were measured on an ASAP2020 type automatic adsorbent (Micromeritics, Inc.). The adsorbent was degassed at 573 K for 3 h, followed by nitrogen adsorption at 77 K. The pore size distribution was calculated by the classical BJH (Barrett, Joyner, and Halenda) methods, while micropore distribution by the H–K method.

The main adsorbent pore structure used is shown in Table 2. S_{BET} of AC-1 is 1486.80 m²·g⁻¹, while it is 805.62 m²·g⁻¹ for AC-2. Sawdust has only a small amount of pores to form specific surface area. AC-1 has both 0.54 nm average micropore diameter and 2.06 nm narrow mesopores. When it comes to AC-2 and sawdust, a shift to larger pore size, with a mesopore of 3.38 nm and 13.11 nm, respectively, will be observed. The pore size of the three adsorbents is consistent with the specific surface area.

3. Results and Discussion

3.1. Removal characteristics of the quench process

In the quench process, the benzene and naphthalene contents in the inlet gas were respectively selected as 281925 mg·m⁻³ and 16408 mg·m⁻³ (according to the feeding conditions). The results are shown in Fig. 3. After cooling, the benzene content changed hardly, while the naphthalene content was significantly reduced. The saturation point of sampling naphthalene vapor was about 80 °C, while the selected cooling temperature was 40–65 °C. Consequently, after the quench scrubber, the naphthalene content in the gas will be reduced.

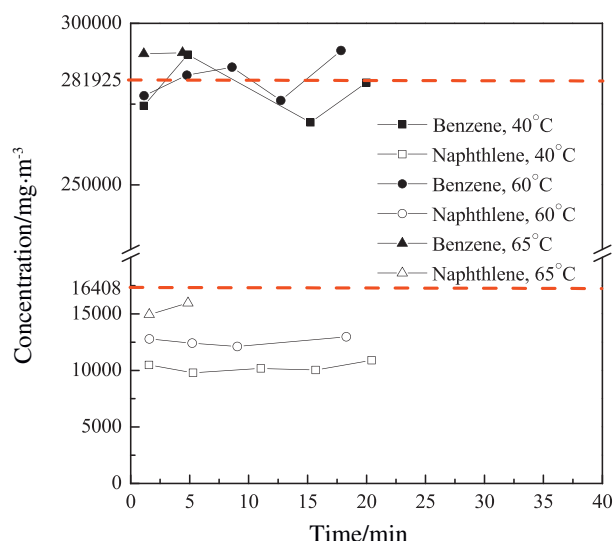


Fig. 3. Removal of benzene and naphthalene during the quenching phase.

The naphthalene content would be decreased with the decreases of the temperature. Regarding benzene, the saturation temperature was lower than 40 °C, so its content was not changed obviously after cooling. For repeated cycling, the heavy tar (naphthalene) will be partially saturated by benzene, so further removal of benzene will lower the corresponding concentration to the dew point. Therefore, for continuous operation, the quenching process mainly acts to cool and condense the heavy tar, as is similar to that of the QCABT for cyclohexane and n-dodecane [6].

To quantitatively analyze tar removal behavior with respect to the quenching temperature, the calculated dew point was plotted and shown in Fig. 4.

Dew point was calculated by the method developed by ECN (<http://www.thersi-tes.nl/completemodel.aspx>).

The dew point of the mixture decreases followed by a decline of the quenching temperature, agreeing with part of naphthalene condensed after the quench scrubber. Saturation temperature of naphthalene, which is consistent with that of the quenching temperature in general, might fluctuate because of uneven heat and mass transfer in the quench scrubber. However, the similar decline tendency shows that naphthalene plays a dominant role in mixture dew point, which is similar to that of QCABT.

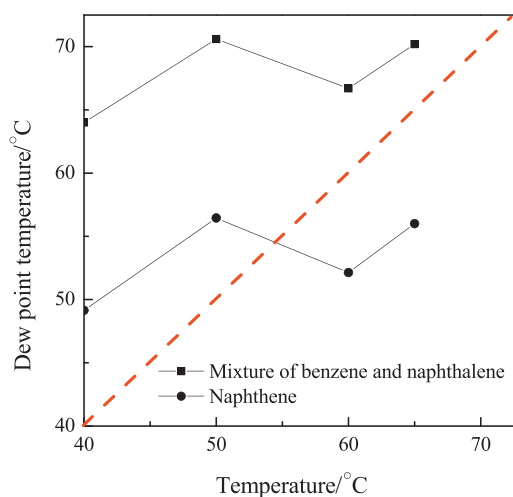


Fig. 4. Dew point variation of naphthalene and benzene–naphthalene mixtures during the quenching phase.

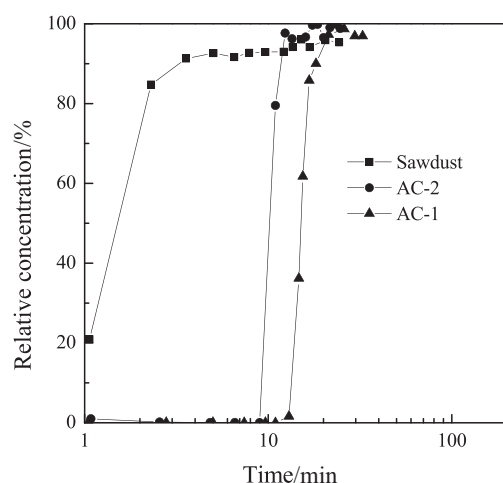


Fig. 5. Dynamic adsorption curve of benzene on adsorbents (30 °C).

3.2. Dynamic adsorption behavior of tar

The adsorbent characteristic is critical to tar removal efficiency. Most tars are non-polar or weak polar aromatic hydrocarbons, so non-polar adsorbents are more preferred. Also, large surface area and abundant pores can promote the nucleation, condensation, and the adsorption effect of high molecular weight aromatic hydrocarbons on the adsorbent. Two types of activated carbon with different pore characteristics were selected. Sawdust is a raw material used in the biomass gasification process. It structurally contains large pores and has the capability to catch tar. Additionally, it can be returned after tar adsorption to the gasifier to be simply burnt in order to recover the energy. Consequently, sawdust was used as the third tar adsorption removal material.

Adsorption dynamic removal performance of benzene and naphthalene was performed, to analyze the association between removal performance and the structure of the adsorbent. The results are shown in Figs. 5 and 6. The benzene concentration was 149167 mg·m⁻³, at an adsorption temperature of 30 °C, while the naphthalene concentration was 16408 mg·m⁻³, at an adsorption temperature of 60 °C (to ensure that naphthalene was adsorbed instead of being condensed).

Fig. 5 shows the dynamic adsorption penetration curve of benzene. The breakthrough curve of activated carbon to benzene was steep. After adsorption, the concentration was lowered to almost 0, indicating that it can significantly remove the simulated tar deeply and reduce the dew point to a safe level. The breakthrough time of benzene on the three

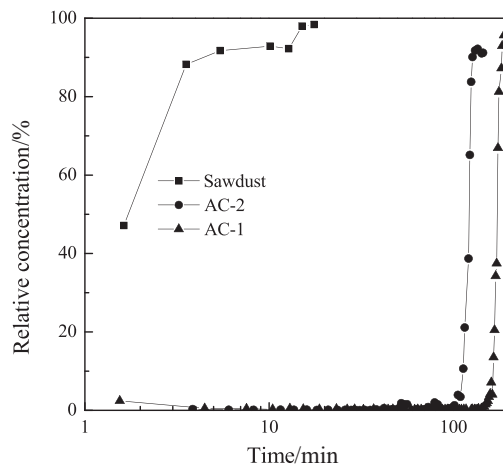


Fig. 6. Dynamic adsorption curve of naphthalene on adsorbents (60 °C).

Table 3
Breakthrough and saturation adsorption loading

Name		Penetration time/min	Adsorption loading/g·g ⁻¹	Saturation time/min	Adsorption loading/g·g ⁻¹
AC-1	Benzene	13	0.3768	21	0.3927
	Naphthalene	160	0.3444	188	0.3732
AC-2	Benzene	9	0.2680	12	0.2963
	Naphthalene	122	0.2576	131	0.2634
Sawdust	Benzene	0	–	15	0.0382
	Naphthalene	0	–	18	0.0158

absorbents gradually decreased from AC-1, AC-2 to sawdust. The breakthrough time on AC-1 was the longest of 13 min and the breakthrough curve was steep indicating a good adsorption performance. The breakthrough time on AC-2 was 9 min, showing a reduced adsorption performance for benzene. The dynamic adsorption curve of sawdust can be transiently broken, implying that it is unable to adsorb benzene. Table 2 shows the different pore characteristics of AC-1, AC-2, and sawdust. AC-1, with the largest surface area, micro-pores, and narrow meso-pores, had the greatest benzene adsorption performance. AC-2 had meso-pores and fairly strong benzene adsorption, with a lowered breakthrough time and saturated adsorption loading. Sawdust had large pores, as was unable to adsorb benzene. As a result, the dynamic curve was broken at a fast speed.

In the adsorption separation process, the pore diameter of the absorbent matches the geometric size of the molecules or ions of the adsorbate. Pores of different sizes can affect the diffusion, synergistic effect of adsorbate molecules and capillary condensation effect. For adsorbing small molecules of low concentration, the surface area sometimes only determines the complete adsorption loading, while only the adsorption force of micro-pores and their pore volume are decisive factors for adsorption performance. In the micro-pore, benzene adsorption occurs in a Langmuir single molecule layer. When the pore diameter exceeds 2–4 nm, multilayer adsorption and capillary condensation effects arise. Therefore, according to the analysis of pore structure characteristics, AC-1 demonstrated the best benzene adsorption.

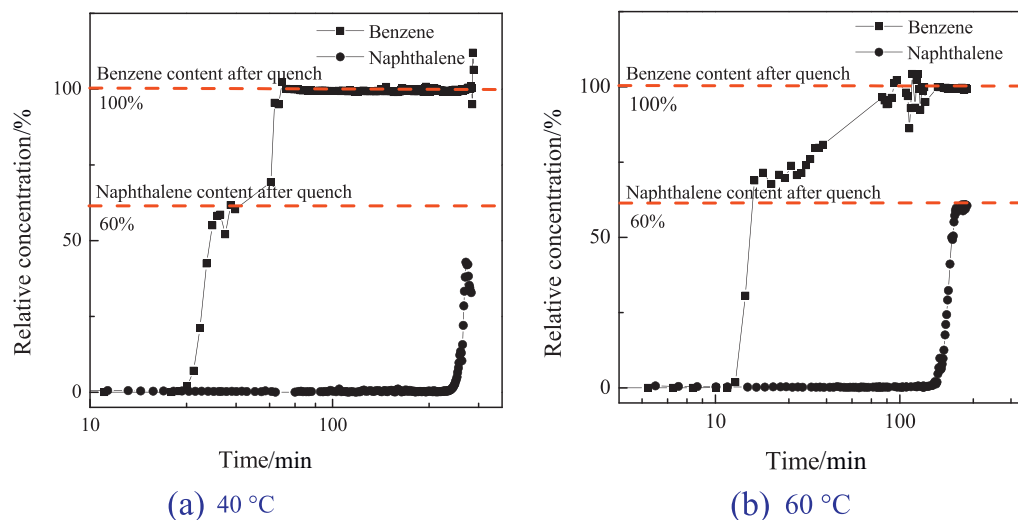
Fig. 6 shows the dynamic adsorption curve of naphthalene. The breakthrough curve of naphthalene is extended along the time axis, which is mainly due to the low concentration of the incoming sample of naphthalene. Adsorption of naphthalene seems more dependent to the specific areas of AC-1 and AC-2 than that of benzene, as shown, meso-pore plays dominant roles in naphthalene adsorption.

With increased molecule diameter, the subjected pore wall superposing action increased, so the diffusion effect in the adsorption process became more significant. This resulted in a lower adsorption rate,

associated with a decreased slope of the adsorption breakthrough curve. The molecule diameter of naphthalene is greater than that of benzene. It is more difficult for naphthalene to diffuse compared to benzene, and this resulted in a gentle breakthrough area. Also, the extremely small micropore reduces naphthalene adsorption. Sawdust had a very short breakthrough time, consistent with its big mesopore characteristics.

The adsorption loadings of the three absorbents were calculated from the breakthrough curves, and the results are shown in Table 3. The adsorption loading was higher for benzene than for naphthalene. For one thing, benzene has a higher concentration than naphthalene. For another, naphthalene has a larger diameter, so that benzene molecules can enter extremely small micro-pore while naphthalene is excluded. AC-1 had the greatest adsorption loading for both benzene and naphthalene, and this was positively correlated to specific surface area. The larger specific area results in higher level of the adsorption. However, this correlation was not proportional, and the increased amplitude of adsorption loading of AC-1 for benzene and naphthalene was less than that of the specific surface area. The adsorption effect of benzene and naphthalene mainly originated from the micro-pores and narrow meso-pores, only these pores are proportional to the adsorption loading. Consequently, such a relationship was not seen with the total specific surface area. For the adsorption of naphthalene, the adsorption curve of AC-2 was steeper, indicating a higher adsorption rate (Fig. 6 and Table 3). Because AC-2 has larger pore sizes, this results in reduced resistance of mass transfer in AC-2 compared to AC-1, providing a shorter time between the breakthrough point to adsorption saturation, hence a higher adsorption rate.

In summary, activated carbon with micro-pores and narrow meso-pores has a high adsorption removal capability for benzene, with the break-through adsorption loading of AC-1 as high as 0.38 g·g⁻¹. For naphthalene, the narrow meso-pores of AC-1 play a dominant adsorption effect with a breakthrough adsorption loading of 0.34 g·g⁻¹. Thus, the micro-pore and meso-pore composite structure is effective

**Fig. 7.** Coupled removal characteristics for naphthalene and benzene of QCADT with AC-1.

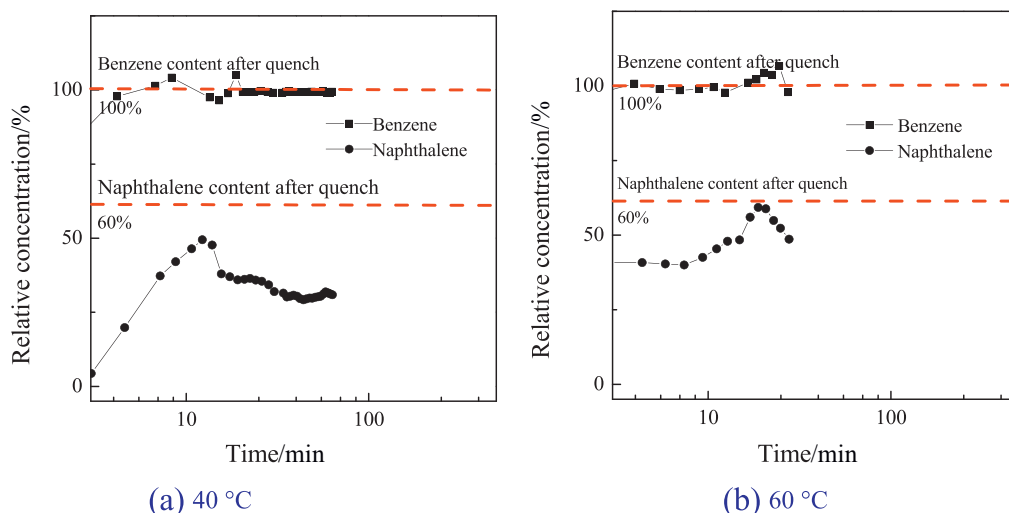


Fig. 8. Coupled removal characteristics for naphthalene and benzene of QCADT with sawdust.

for the deep removal of tar, and also for the diffusion of tar molecules, leading to a higher removal efficiency. Char-coal and sawdust can remove heavy tar and then be directly returned for gasification. These materials can be used in rough tar extraction, to reduce the load of subsequent deep tar elimination. Activated carbon rich with micropores and narrow meso-pores must then be used for more completely removal of benzene and other one-ring aromatic hydrocarbon light tars.

3.3. Coupled removal performance of tar

Quenching unit and adsorption unit were connected in series to investigate the coupled removal characteristics and competitive adsorption behavior. Benzene feeding concentration is $149167 \text{ mg} \cdot \text{m}^{-3}$, and a naphthalene feeding concentration of $16408 \text{ mg} \cdot \text{m}^{-3}$, at a cooling temperature 50°C and adsorption temperatures ranging from 40°C to 60°C .

The results are shown in Figs. 7–9. The benzene concentration did not drop in the cooling process, as shown, benzene was not removed in the cooling phase. After the cooling process, the naphthalene concentration decreased to 60% of the feeding content, i.e. the naphthalene saturation point corresponding to 50°C . These results are consistent with the tar removal characteristics in the quenching process.

In the adsorption process, the 60°C adsorption temperature was higher than the saturation temperature of naphthalene feeding. The break-through time of AC-1 and AC-2 for benzene was similar at about 20 min. When the adsorption temperature increased, the break-through time was slightly shortened. The sawdust breaks through benzene transiently, indicating that it hardly has any benzene adsorption ability. After the outlet benzene concentration became saturated for about 110 min, the ridge for naphthalene occurs. During the adsorption process, a peak was formed in the adsorption breakthrough curve of benzene, which is typical competitive behavior. The benzene and naphthalene peaks appeared in succession, and when the naphthalene peak appeared, the benzene peak showed a temporary increase followed by a decrease. This result occurred because the adsorption affinity of components was different in a multicomponent system, and the equilibrium distribution between the moving phase and stationary phase for each component was different. Also, because of the limited active points on the absorbent surface, competitive adsorption exists. A compound with a high bonding force to the adsorbent can be readily absorbed and can be referred to as a strong adsorbate. In our system, naphthalene was a strong adsorbate while benzene a weak one. In the adsorption process of a multi-component system, the strong adsorbate is adsorbed at the front end, while the weaker adsorbate, because of weak

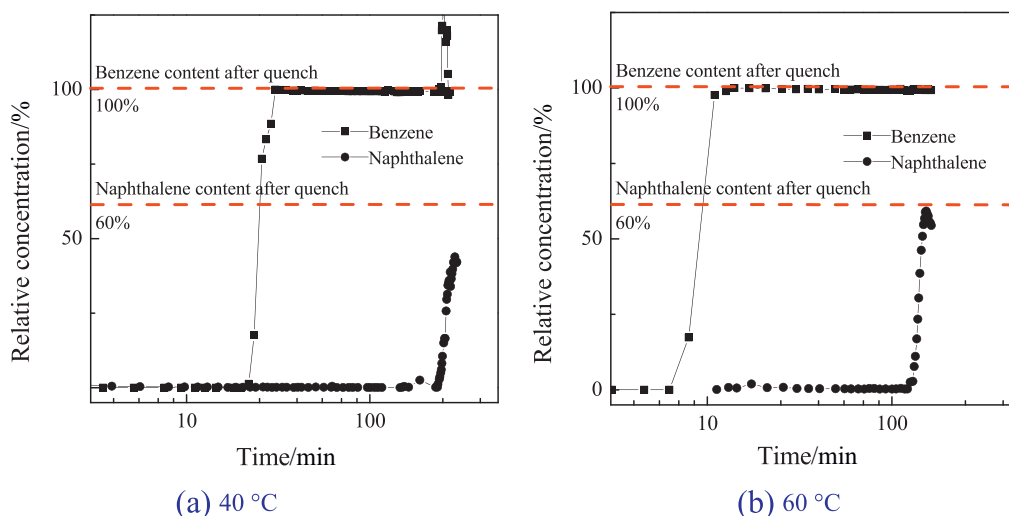


Fig. 9. Coupled removal characteristics for naphthalene and benzene of QCADT with AC-2.

competitive adsorption ability, will move with the main body of adsorbate to the rear end of the adsorption column. With the forward movement of strong adsorbate, the weak adsorbate already adsorbed at the rear end of the adsorption column is substituted out, to be mixed with the weak adsorbate in the feed gas. This is seen as the weak adsorbate concentration being higher than the feed concentration and exceeding 100%, i.e., a peak appears.

In cases where the adsorption temperature is lower than the quench temperature, the adsorption unit has some cooling effect in addition to adsorption, as demonstrated by extended break-through time. The breakthrough time is extended to about 250 min for AC-1 and about 200 min for AC-2. Even for sawdust, having little adsorption of naphthalene, also develops some ability to remove naphthalene. Both AC-1 and AC-2 can completely remove naphthalene before the breakthrough zone. Sawdust has some cooling and intercepting effect, but its adsorption is broken at a rapid speed through resulting in loss of tar removal ability.

Both AC-1 and AC-2 can completely remove naphthalene before the breakthrough zone, and this can produce deep tar removal and cleaning of fuel gas. The sawdust is almost transparent for removing tar, especially for benzene-like light tar. However, it can be designed to remove part of heavier tars than naphthalene before real adsorption occurs. Considering the excellent benzene removal capability of AC-1, owing both big micro-pore and narrow meso-pore, is promising for tar removal.

4. Conclusions

Benzene and naphthalene were selected as the light and heavy simulated tar, respectively. Three typical porous materials were used as adsorbents to investigate the mechanism of the novel QCADT. The main results are as follows:

- (1) The quenching section of QCADT plays a dominant role in naphthalene removal, while hardly any effect for benzene, which is similar to that of QCABT, except for the higher overall tar removal rate of QCADT due to adsorption effect.
- (2) Adsorbents with micro- and narrow mesopores exhibit a better benzene removal performance, while narrow mesopores have significant effects on naphthalene removal. Break-through adsorption loading of benzene and naphthalene on AC-1 can reach $0.38 \text{ g} \cdot \text{g}^{-1}$ and $0.34 \text{ g} \cdot \text{g}^{-1}$, respectively.
- (3) The sawdust hardly has any tar removal effect, especially for benzene-like light tar, due to its economic feasibility and recovery.

Combined micro- and meso-pore structure of the adsorbents will benefit both deep tar removal and large adsorption rate, providing a high tar removal efficiency.

References

- [1] S.K. Sansaniwal, K. Pal, M.A. Rosen, S.K. Tyagi, Recent advances in the development of biomass gasification technology: A comprehensive review, *Renew. Sust. Energ. Rev.* 72 (2017) 363–384.
- [2] S. Anis, A. Zainal, Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods — A review, *Renew. Sust. Energ. Rev.* 15 (2011) 2355–2377.
- [3] N.S. Bobbitt, M.L. Mendonca, A.J. Howarth, T. Islamoglu, J.T. Hupp, O.K. Farha, Metal-organic frameworks for the removal of toxic industrial chemicals and chemical warfare agents, *Chem. Soc. Rev.* 46 (2017) 3357.
- [4] J. Wu, H.J. Chen, Y.Z. Zhu, C.H. Liao, L. Yang, Biomass producer gas tar removal technology based on recovery idea, (in Chinese) *Ind. Eng. Prog.* 32 (2013) 2099–2105.
- [5] M.J. Salar-García, V.M. Ortiz-Martínez, F.J. Hernández-Fernández, A.P.D.L. Rios, J. Quesada-Medina, Ionic liquid technology to recover volatile organic compounds (VOCs), *J. Hazard. Mater.* 321 (2016) 484–499.
- [6] H.J. Chen, J. Wu, X.Y. Wang, Y.Z. Zhu, L. Yang, H. Wu, Z.Q. Chen, C. Zhang, L. Wan, Simulated biomass tar removal mechanism and performance by a quench coupled with absorption technology, *Fuel Process. Technol.* 146 (2016) 90–98.
- [7] L.P.L.M. Rabou, R.W.R. Zwart, B.J. Vreugdenhil, L. Bos, Tar in biomass producer gas, the energy research Centre of The Netherlands (ECN) experience: An enduring challenge, *Energy Fuel* 12 (2009) 6189–6198.
- [8] T. Phuphuakrat, T. Namioka, K. Yoshikawa, Absorptive removal of biomass tar using water and oily materials, *Bioresour. Technol.* 2 (2011) 543.
- [9] The Energy Center of the Netherlands, BioSNG: Ongoing activities, <http://www.biosng.com/ongoing-activities/>.
- [10] F.C. Chu, Y. Zheng, B.Y. Wen, L. Zhou, J. Yana, Y.L. Chen, Adsorption of toluene with water on zeolitic imidazolate framework-8/graphene oxide hybrid nanocomposites in a humid atmosphere, *RSC Adv.* 8 (2018) 2426–2432.
- [11] P. Anchan, N. Shota, K. Masataka, P. Pandji, Y. Kunio, Performance of tar removal by absorption and adsorption for biomass gasification, *Fuel Process. Technol.* 104 (2012) 144–154.
- [12] T. Phuphuakrat, T. Namioka, K. Yoshikawa, Tar removal from biomass pyrolysis gas in two-step function of decomposition and adsorption, *Appl. Energy* 7 (2010) 2203–2211.
- [13] T. Tampradab, S. Unyaphan, F. Takahashi, Tar removal capacity of waste cooking oil absorption and waste char adsorption for rice husk gasification, *Biofuels* 4 (2013) 401–412.
- [14] A. Paethanom, S. Nakahara, M. Kobayashi, Performance of tar removal by absorption and adsorption for biomass gasification, *Fuel Process. Technol.* 12 (2012) 144–154.
- [15] A. Paethanom, P. Bartocci, B.D. Alessandro, A low-cost pyrogas cleaning system for power generation: Scaling up from lab to pilot, *Appl. Energy* 11 (2013) 1080–1088.
- [16] Y.F. Shen, Chars as carbonaceous adsorbents/catalysts for tar elimination during biomass pyrolysis or gasification, *Renew. Sust. Energ. Rev.* 43 (2015) 281–295.
- [17] Y. Xiao, H.R. Yuan, Y.Z. Pang, S.L. Chen, B.N. Zhu, D.X. Zou, J.W. Ma, L. Yu, X.J. Liu, CO₂ removal from biogas by water washing system, *Chin. J. Chem. Eng.* 8 (2014) 950–953.
- [18] Y. Z. Zhu, H. J. Chen, J. Wu, and C. H. Liao, The Biomass Gas Tar Removal System of the Self-cooling Coupled with Adsorption Technology, CN Pat., ZL 201210037246.7 (2012). (in Chinese).
- [19] Z.Q. Chen, X.S. Zhang, R.J. Cheng, Q. Cui, H.J. Chen, Y.Z. Zhu, The characteristic of biomass gas tar removal by a quench coupled with adsorption process, (in Chinese) *Sci. Sin. Tech.* 47 (2017) 763–773.