Effects of bed aging on temperature signals from fixed-bed adsorbers during industrial operation

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ABSTRACT

The capacity of adsorber beds used in industrial-scale temperature-swing adsorption diminishes over time due to bed aging. Here, we present industrial data on the temperature signals from fixed-bed adsorbers using activated carbon designed to remove benzene and other impurities from the gas produced in biomass gasification. The aging of the adsorber beds proceeds due to irreversible adsorption of trace species and manifests itself via two simultaneous effects: a decrease in the availability of active adsorption sites over time and an increase in the overall thermal mass of the bed. Both effects tend to dampen the temperature response of the beds during operation, implying that they are easily confounded. Model descriptions of bed aging should account for both effects.

1. Introduction

Temperature-swing adsorption onto activated carbon is a common industrial technique for removal of benzene and other impurities from the product gas produced in biomass gasification [1,2]. The adsorption process operates by using several adsorber beds that alternate between being active for adsorption and being regenerated by a hot inert purge gas (e.g. steam) [3]. The adsorber beds are typically designed for the removal of one specific component from the gas phase, even though the gas composition may also include other species with varying affinity for the surface. Furthermore, it is customary to only account for the fresh state of the bed. In reality, the beds will slowly fill up with irreversibly adsorbed trace species that do not desorb during the regeneration stage. Consequently, the carbon has to be replaced after some time of operation. Knowledge about the bed behavior during this slow degradation process is needed for the development of models for bed aging, which may be useful in the design and optimization of the process layout and operation. To the authors' knowledge, there is currently no data available in the open literature on the thermal response of aged adsorber beds from industrial-scale temperature-swing adsorption of complex gas mixtures, such as those produced in biomass gasification.

2. Methodology

We have recorded a large industrial data set from a first-of-its-kind wood-based biomethane production plant located in Gothenburg, Sweden (comprising a 32-MW_{th} dual fluidized bed (DFB) gasifier, complemented by synthetic natural gas (SNG) synthesis producing up to 20 MW of biomethane) [2]. This plant has in total four adsorber beds (i.e. cylindrical containers packed with activated carbon) for removal of mainly benzene (but also naphthalene, toluene, xylene and other substances). The gas is led through the bed, where benzene adsorbs to the carbon and is thus removed from the stream. The activated carbon used is tailored to benzene removal and the main bed and gas characteristics are summarized in Table 1.

The time that a bed spends in adsorption or regeneration modes varies depending on the fuel used, operational state and whether breakthrough occurs. Therefore, the results from the industrial data

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Table 1

Properties of the active carbon beds and the gas flow through them during adsorption, regeneration and cooling.

Bed	
Carbon type	WS-490, Chemivron
Bed radius	1.375 m
Total mass of carbon	4.5 ton
Bed bulk density	390 kg/m^3
Characteristic particle size	6 mm
Gas	
Typical gas composition into the bed	H_2 – 39 mol%
	CO – 23 mol%
	CO_2 – 24 mol%
	CH_4 – 9 mol%
	C_2H_x – 2.3 mol%
	C_6H_6 – 10 g/Nm^3
Typical conditions	Velocity: 0.3 m/s
Active stage (adsorption)	Temperature: 320 K
	Pressure: 1 bar Duration: 5–6 hours
Typical conditions	Velocity: 0.014 m/s
Regeneration stage (desorption)	Temperature: 432 K
	Pressure: 4 bar Duration: 4 hours
Typical conditions	Velocity: 0.09 m/s
Cooling stage (adsorption)	Temperature: 320 K
	Pressure: 1 bar Duration: 4–5 hours

Fig. 1. Comparison between temperature signals from industrial cycling of carbon beds of. Different age in (a) the bottom position and (b) the top position. During adsorption, the gas mixture enters from the bottom, and during regeneration, steam enters from the top.

presented are selected to represent typical operating conditions. The results are averaged over a number of days when operation was stable, with a consistent throughput.

Each bed in the plant had temperature sensors mounted inside the carbon to monitor the current state. Here, we present data from the bottom-most and top-most sensors, positioned at distances of 0.40 and 1.55 m from the bottom of the bed, respectively (the total bed height is 1.9425 m). Since adsorption is an exothermic process and desorption an endothermic one, the temperature of the bed increases in the region where adsorption takes place and decreases where desorption occurs. Also steam condensation and evaporation influence the temperature signal. Most notably, the bed is heated by the hot steam during the regeneration step (cf. Table 1).

3. Results and discussion

Fig. 1 illustrates the temperature signals during one adsorption-regeneration-cooling cycle from two beds that have been online in the industrial process for a different amount of time. The first 320 minutes represent adsorption, the temperature increase thereafter (lasting until approximately 600 minutes) is indicative of regeneration, and the last segment constitutes cooling of the bed (with simultaneous adsorption). The pattern repeats itself continuously as the beds are operated in a cyclic regime. Because of a slow build-up of irreversibly adsorbing substances that degrade the capacity of the beds, and the fact that beds are replaced at different points in time, the cycling behavior becomes different from bed to bed.

When comparing the two beds, the first observation is that the older bed does not exhibit the same extremes as the newer bed. Firstly, the temperature peaks during cooling, which occur as the adsorption front moves past the thermocouple position, are lower (cf. Fig. 1a at around 700 minutes). Secondly, the heating at the upper position during the active phase (again due to the passage of the adsorption front) is less pronounced, and the lowest temperatures observed are slightly higher than those in the newer bed (cf. Fig. 1b at 50–300 minutes). We attribute these effects to the irreversible adsorption of substances other than benzene. On the one hand, such non-regenerable substances partially occupy the adsorption sites. Fewer available sites mean that less substance will adsorb to the carbon during a cycle, therefore releasing or requiring less heat. On the other hand, the density of the carbon increases during the lifetime of the bed due to these non-regenerable substances (the analyses of the carbon beds when they are eventually discarded,
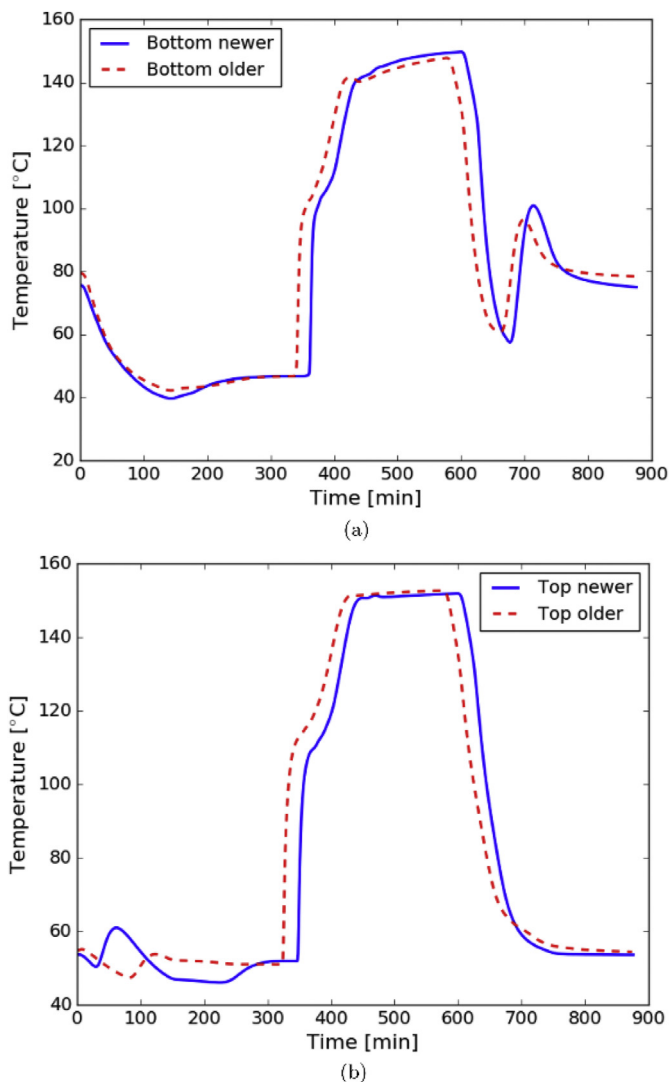
after also having served as a pre-filter, reveal density increases of 22–58%). More thermal mass, given the same energy release or consumption from adsorption, also yields lower temperature swings. It is clear that the presence of irreversibly adsorbing substances dampens the thermal behavior of the bed, and that this phenomenon leads to two distinctively different effects, which should thus both be accounted for in mathematical models that aim at predicting the correct temperature-swing behavior.

4. Conclusions

Data was presented on the effects of aging in industrial-scale temperature-swing adsorption for gas cleaning in biomass gasification. Aging of the adsorber beds was shown to influence the thermal behavior via irreversible adsorption, which decrease the availability of free adsorption sites and increases the thermal mass of the system. We believe that future model developments that describe the effects of bed aging should include both these effects, and that the industrial data presented herein may form a basis for future validation of such model descriptions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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