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Understanding of mass transfer resistance for the adsorption of solute onto porous material from the modified mass transfer factor models

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HIGHLIGHTS

- Many models and theories have been developed for specific purposes.
- Generalized model under certain conditions is important for the issues.
- This study proposes the modified models to determine the resistance of mass transfer.
- The adsorptions of NH_4^+ and Al^{3+} onto granular activated carbon from surface water were studied.
- The paper presents a new approach to investigate mass transfer resistance.

GRAPHICAL ABSTRACT

Adsorption mechanisms of solute onto porous material from water can be determined using the modified mass transfer factor models.

$$\ln\left(\frac{C_o}{C_s}\right) = [k_L a]_g \times e^{-\beta \times \ln(q)} \times t$$

↓

$$\ln(q) = B + \frac{1}{\beta} \times \ln(t)$$

↓

$$B = \frac{\ln([k_L a]_g) - \ln\left\{\ln\left(\frac{C_o}{C_s}\right)\right\}}{\beta}$$

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ABSTRACT

Mass transfer is important in separation and is essential for adsorption process. Mass transfer resistance controls the adsorption kinetic rate, but there is only limited understanding of the adsorption of a solute onto porous material from surface water. This study investigates the adsorptions of NH_4^+ and Al^{3+} onto granular activated carbon from surface water using the laboratory-scale plug flow column. The use of the modified mass transfer models is able to determine the resistance of mass transfer for the adsorption of one or more solutes present in surface water onto porous material. In this case study identified that the resistance of mass transfer is dependent on film mass transfer before and porous diffusion after breakthrough occurred. The research findings advance understanding of novel approach for investigating mass transfer resistance of solute onto porous material from waters.

1. Introduction

In the pass years, Sembrong Lagoon served as an important water supply resource for the district of Batu Pahat in Johor state, Malaysia. Water from the lagoon flowed through two separate pipes directly to the Sri Gading Water Treatment Plant (SGWTP) and Unit 4 Parit Raja Water Treatment Plant (U4PRWTP) that treated raw water to produce drinking water. The lagoon obtains freshwater pumped or fed by gravity from surface supplies from Bekok River or small canals of rainwater collector. Unfortunately, such exploitable water resource used for public drinking water supplies today is not of suitable quality for human consumption without some forms of advanced treatment. It has been suggested that poor water quality is due to the excess amount of certain solutes such as NH_4^+ and Al^{3+} in the raw water does not achieve the admissible performance level of conventional water treatment plant to produce drinking water. Chemical clarification for the removal of NH_4^+ and Al^{3+} has been practiced at SGWTP; however, the levels of NH_4^+ and Al^{3+} in treated water did not meet the drinking water quality standards regulated by law [1]. Adsorption is one of the alternative treatment processes for removing NH_4^+ and Al^{3+} from waters. Granular activated carbon (GAC) is the most popular and versatile adsorbent and has traditionally been used in the removal of scent,

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Nomenclature

a	surface of interfacial liquid–solid (m^{-1})
B	potential mass transfer index relating to driving force of mass transfer ($mg\ g^{-1}$)
C_o	concentration of the adsorbate to entry to the column ($mg\ L^{-1}$)
C_s	concentration of the adsorbate to depart from the column ($mg\ L^{-1}$)
k_L	mass transfer coefficient ($m\ h^{-1}$)
$[k_La]_d$	porous diffusion factor or internal mass transfer factor (h^{-1})
$[k_La]_f$	film mass transfer factor or external mass transfer factor, or volumetric film mass transfer coefficient (h^{-1})
$[k_La]_g$	global mass transfer factor (h^{-1})
q	accumulative quantity of the solute adsorbed onto GAC ($mg\ g^{-1}$)
t	accumulation time (h)
β	adsorbate–adsorbent affinity parameter ($g\ h\ mg^{-1}$)

taste and colour caused by the presence of pollutants in waters [2]. The removal of NH_4^+ and Al^{3+} from waters by adsorption onto GAC has been studied extensively [3,4]. Still, mass transfer resistance must be properly considered in the separations of solutes from waters by adsorption process and needs to be verified.

Many models and theories that have been developed are valid for specific purposes [5–8]. For example, the mass transfer factor models as proposed by Fulazzaky [9] are valid for determining the resistance of mass transfer for the adsorption of a single solute onto granular activated carbon (GAC) from aqueous solution. Due to the fact that surface water contains many different solutes, the proposed models [9] cannot describe the mechanisms of competitive adsorption of two or more solutes to be much more complex than single solute. Mechanism of the adsorption of a solute onto porous material in aqueous solution can be represented by three successive steps, i.e., film mass transfer, porous diffusion and then fixation [9,10]. Both film mass transfer and porous diffusion might control the adsorption kinetic rate since quick fixation of solute at acceptor sites of the adsorbent no influences on the resistance of mass transfer. The mass transfer equation should have wide applications for determining the removal of mixed solutes together from waters and is the governing principle of solutes migration in separation techniques. For example, the removal of NH_4^+ and Al^{3+} from waters by adsorption onto GAC can adsorb together with other solutes. The advantage of mass transfer models can provide an explicit framework for understanding further improvement of the adsorption capacity, adsorbate–adsorbent affinity and other properties need for wide applications.

This research project focused to perform a detailed systematic adsorption study of NH_4^+ and Al^{3+} due to the excessive amounts of these two solutes in the water supply resource are difficult to be treated conventionally for potable water. They were the quality indicators to be used for evaluating the effectiveness of the remedial strategies on the reduction of pollutants loading the SGWTP and U4PRWTP in the district of Batu Pahat, Malaysia, in the past decade. The main objective of this study was to improve the knowledge of multi-solute adsorption and its importance in removing of NH_4^+ and Al^{3+} from surface water for the application of GAC as adsorbent in cleaning up low quality natural waters for drinking water production.

2. Materials and methods

2.1. Adsorbent

This study used the commercial GAC as adsorbent named the "granular activated carbon type 8 × 30 special water" originally delivered from Effigen Carbon Sdn. Bhd., Kapar, Selangor, Malaysia. Coconut shell charcoal is the raw material required for the manufacture of the GAC. The physical properties of the GAC are depicted in Table 1.

2.2. Adsorbate/solute

In this case study, it is possible to count that a number of solutes such as Ca^{2+}, K^+, Al^{3+}, O_2, CO_2, HCO_3^-, CO_3^{2-}, NH_4^+, NH_3, NO_3^-, Cl^-, SO_4^{2-}, PO_4^{3-}, organic matters and certain heavy metals as well as certain microorganisms were present in the water sample [11–13]. Therefore, many factors must be considered when selecting the appropriate adsorbate to be studied for the adsorption of a solute onto GAC from surface water. This study focused on the adsorptions of two solutes (i.e., NH_4^+ and Al^{3+}) differing by their concentrations in the water sample can determine the effect of concentration on partitioning of acceptor sites on the GAC surface during the adsorption process.

2.3. Experimental instrument

A glassy plug flow column in vertical position filled with 500 g GAC was used as the experimental instrument, as shown in Fig. 1. The adsorption capacity of GAC in the column can remove a number of solutes including NH_4^+ and Al^{3+} and varies widely, depending on the quality of the water sample. Still this research only focused on the adsorption of NH_4^+ and Al^{3+} onto GAC from the surface water in dynamic regime [14]. A crucial factor discovered during the experiments was to ensure the flow rate to be maintained at a constant [15]; therefore, -the water sample to flow from the water storage tank to column in a downward direction was regulated using the peristaltic pump to maintain a constant flow rate of 22.4 $cm^3\ h^{-1}$. The dimensions of the column are depicted in Table 2. Both the concentrations of NH_4^+ and Al^{3+} were monitored at outlet of the column with an interval of 1 h. The water sample that stored in the water storage tank has the concentrations of NH_4^+ and Al^{3+} as high as 1.68 $mg\ L^{-1}$ and 3.45 $mg\ L^{-1}$, respectively. In this typical experimental run, a 200 L water sample from Sembrong Lagoon was used as feed water to flow continuously through the column in a vertical position. Once the GAC has been saturated with NH_4^+ and Al^{3+}, it needs to stop the running experiment.

Table 1
Physical properties of the GAC.

Physical property	Unit	Value
Origin (raw material)		Coconut shell
BET surface area	m^2/g	1076
Density	g/cm^3	0.49
Mesh size 8 × 30	mm	96.17
Moisture content	%	2.96
Ash content	%	2.32
Hardness	%	98.17
pH		9.89