# C113 ADSORPTION RATE MAESUREMENTS OF ACTIVATED CARBON FIBER/ETHANOL PAIR FOR ADSORPTION COOLING SYSTEM APPLICATION

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# ABSTRACT

Adsorption kinetics of ethanol onto a pitch-based activated carbon fiber (ACF) of type (A-20) is studied. Instantaneous uptake as well as the adsorbent temperature is measured by using a thermal-gravimetric analyzer (TGA) unit. The measured mass and temperature are logged with a time interval of 0.5 second which makes it possible to have a continuous change of mass of adsorbed ethanol with time. Experiments have been carried out across assorted adsorption temperatures that are useful to the operation of adsorption chillers. System pressure is maintained constant during the experiments by a vacuum pump and a pressure-feedback modulating valve. Overall mass transfer coefficient has been evaluated by matching the experimental uptake with the linear driving force (LDF) equation. Comparison between the experimentally measured data and the predicted results of adsorption rate shows a good agreement, demonstrating the adsorption rate is mainly controlled by the surface diffusion.

Keywords: Activated carbon fiber, Adsorption rate, Ethanol, Heat and mass transfer.

# **1. INTRODUCTION**

Activated carbon fibers (ACFs) have many intrinsic characteristics that are superior as compared with the palletized or granular activated carbon fiber, for example, the large surface area, fast inter-particle adsorption kinetics [1, 2] and ease of handling especially when they are used in belt or foam forms. Therefore, they have been used in many applications such as gas separation, gas storage and catalytic reactions. Recently, several studies have been conducted to investigate the potential types of ACFsrefrigerant pairs for adsorption cooling or heat pump applications [3-5]. The uptake behavior of ACF (A-20)/ethanol pair seems to be a promising pair for cooling applications. Besides the high affinity for ethanol, the salient features of ACF (A-20) are; a high surface area of about 1.9  $\times 10^6$  m<sup>2</sup>/kg, a pore volume of 10.28 $\times 10^{-4}$ m<sup>3</sup>/kg and a suitable average pore diameter of approximately 21.6 Å [6, 7].

To improve the performance of adsorption cooling systems, it is essential to determine the kinetics of adsorbent/adsorbate (refrigerant) pair. However, design and modeling of adsorption processes require numerical solution of a set of partial differential equations involving time and special variables. The computations can be greatly simplified by using linear driving force (LDF) method [8]. Conventionally, the computations time of the code could be optimized using the well-known linear driving force (LDF) correlation. In the LDF method, the key parameter is the determination of the overall particle mass transfer coefficient which is can be estimated by tracking the experimental vapour-uptake bahaviour.

In this paper, the adsorption rates of ethanol uptake onto the adsorbent ACF (A-20) for an assorted range of temperature have been measured which corresponds to useful temperatures expected of the operation of adsorption chillers, namely between 27 and 60°C, respectively. Using a thermal-gravimetric analyzer (TGA) unit, instantaneous uptake measurements as well as the adsorbent temperatures are accurately recorded at regular time interval of 0.5 second. The chamber pressure of adsorbent is maintained constant during the experiments by a vacuum pump and a pressure-feedback modulating valve.

#### 2. EXPERIMENTS

Figure 1 shows schematic diagram of the experimental apparatus which comprises the TGA (Cahn TG 2121) unit, a water-heated evaporator, and a vacuum pump with a modulating valve. To measure the adsorption temperature, a thermocouple of type K is inserted into the reacting chamber near to the bottom of the adsorbent or sample pan where both the adsorbent and temperature sensor would be exposed to the same heater. The system pressure is chamber pressure. The controller then operates modulating

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1: Reacting Chamber; 2: Helium injection port 3: Gas flow regulating valve; 4: Microbalance; 5:Porous mesh (damper); 6: Valve; 7: Pressure regulating valve; 8: Vacuum pump connection; 9: Water circulator 10: Water bath; 11: Evaporator; 12: Heater; 13: Thermocouple; 14: Pressure sensor; 15: Sample pan; 16: heater

Fig. 1. Schematic diagram of the experimental apparatus.

vacuum valve. A diaphragm type vacuum pump is used to evacuate the system continuously operating in concert with the pressure sensor and controller so as to maintain a pre-set chamber pressure condition. Fine porous meshes are mounted at the inlet and exit of the adsorbent chamber which provide damping for any pressure fluctuations arising from the modulating actions. During experiment, the microbalance unit of the TGA is protected from any reactive gas by introducing a small amount of helium gas, which is injected from the top of the dome-shaped cover. As the adsorbate is a condensable vapour, condensation is prevented by raising the tube and chamber wall temperatures, using an externally wrapped electric tape-heater.

A series of experimental runs have been carried out at different adsorption temperatures within a range from 27 to 60°C. The evaporator, containing the liquid ethanol, is kept constant temperature at 15°C by a temperature adjustable bath. Samples of ACF, typically about 71 mg in weight, are inserted into the reactor chamber of the TGA unit. Prior to each adsorption experiment, the sample is first regenerated under vacuum conditions but adsorbent is maintained at a temperature of 140°C for several hours to ensure complete desorption. Gases extraction from the reacting chamber is conducted from the top section where it minimizes the mixing of ethanol and helium gas. Separation of gases is also aided by the lower density of the helium gas.

Adsorption experiments commence when the evaporator (containing ethanol) valve is opened and ethanol vapour flows slowly to the reacting chamber through a porous plug. The system pressure is observed to increase from an initial pressure of 18 mbar (the lowest possible chamber pressure due to helium injection) to 32 mbar within a period of only 60 seconds and the chamber pressure remains constant throughout the adsorption experiment. The mass of adsorbed ethanol and the adsorbent temperatures are sampled and recorded at 0.5 second interval until the equilibrium conditions is attained.

#### 3. RESILTS AND DISCUSSIONS

Figure 2 shows the instantaneous ethanol uptake onto ACF (A-20) for 7 sets of isotherms by the TGA and the data are recorded at 0.5 second interval.

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Fig. 2 Ethanol uptake on ACF (A-20) with time at assorted adsorption temperatures.

At low temperature of 27°C, the equilibrium uptake is achieved at 67% by mass within 2700s. Similar asymptotic behavior is also observed for isotherms 28°C and 31.5°C. As expected, the equilibrium ethanol uptake decreases with increasing temperatures. The TGA data, recorded at short time interval, makes it possible to estimate the experimental adsorption rate accurately throughout the transient.

In the present study, the overall mass transfer coefficient is determined by using the well known linear driving force (LDF) equation [9] which is shown in Eq. (1). Where, adsorption rate,  $\partial w/\partial t$ , is determined using the finite difference technique with a time interval as small as 0.5 s It is found that, the overall mass transfer coefficient is nearly constant within the selected range of time for constant adsorption temperature (see Fig. 3) However, it increases with the increase of adsorption temperature. This is because the overall mass transfer coefficient is function of the surface diffusion (Eq. 2), which follows Arrhenius law.

$$\frac{\partial w}{\partial t} = k_s a_v \left( W - w \right) \tag{1}$$

$$k_s a_v = \frac{F_0 D_s}{R^2} \tag{2}$$

The surface diffusivity  $D_s$  can be expressed as:

$$D_s = D_{so} \exp\left(\frac{-E_a}{R_e T}\right) \tag{3}$$

Multiplying both sides of Eq. (3) by  $F_0$  one can get,



Fig. 3. Change of overall mass transfer coefficient with time at different adsorption temperatures.



Fig. 4 Arrhenius plot of ACF(A-20)/ethanol pair.

$$F_0 D_s = D_0^* \exp\left(\frac{-E_a}{R_e T}\right) = D_{eff}$$
(4)

Where  $D_{eff}$  is the effective surface diffusivity. By fitting  $\ln(D_{eff})$  versus 1/T which is shown in Fig. 4, it is found that the numerical value of the pre-exponential constant  $D_0^*$  is found to be  $2.228 \times 10^{-11}$  and the activation energy,  $E_a$  is 304.7 kJ/kg within the selected adsorption temperature and time ranges. Clausius–Clapeyron equation is used to evaluate the average value of heat of adsorption. It is found that the average value of heat of adsorption to be about 1006 .kJ/kg [10]. This implies that the activation energy is about 30% of the heat of adsorption. It was reported that the percentage of activation energy is about 0.3 to 1.0 of the heat of adsorption [11].



Fig. 5. Percentage of error between the measured and calculated adsorption rates

Figure 5 shows the percentage of error between the measured and calculated adsorption rates. The measured adsorption rates are determined by applying a finite difference calculation on the TGA data whilst the predictions are obtained by the LDF equation. A relatively good agreement for the adsorption rates is observed and the maximum percentage error for the bulk of data (from 7 isotherms) is found to be  $\pm 10\%$ .

### 4. CONCLUSION

The main conclusions are as follows:

- The adsorption rate of ethanol onto ACF (A-20) has been successfully measured using the TGA over a wide range of adsorption temperatures, typically between 27 and 60°C, which is useful for the processes of adsorption chillers.
- 2-) Experimental results show that there is no significant change of the overall mass transfer coefficient with adsorption time. However, it increases with the increases of adsorption temperature.
- 3-) Activation Energy is evaluated by using Arrhenius law and it is found that the activation energy is about one third of heat of adsorption within the selected ranges of adsorption temperature and time.
- 4-) Comparison between the experimentally measured data and the predicted results of adsorption rate shows a relatively good agreement and the maximum percentage error for the bulk data (from 7 isotherms) is found to be less than  $\pm 10\%$ .

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# NOMNECLUTURE

- $D_s$  Surface diffusion coefficient  $[m^2/s]$
- $D_{eff}$  Effective surface diffusion coefficient [m<sup>2</sup>/s]
- $D_0^*$  Pre-exponential constant used in Eq. (4)
- E<sub>a</sub> Activation energy [kJ/kg]
- $F_0$  Constant used in Eq. (1)
- $K_{s}a_{v}$  Overall mass transfer coefficient [s<sup>-1</sup>]
- R Fiber radius [m]
- $R_e$  Gas constant [kJ/kg·K]
- t Time [s]
- T Temperature [K]
- *w* Instantaneous adsorption capacity [kg/kg]
- W Equilibrium adsorption capacity[kg/kg]

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