Role of chemical equilibrium on the performance of an activated carbon–methanol adsorption refrigeration tube

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Abstract. The main compartment that determines the functionality of the adsorption refrigerator is the adsorption refrigerator tube (ART). Many scientists have suggested certain ART configuration that would help improve its adsorption performance. The focus of the research is to determine causes of the ART malfunction via material failure. The linear driving force (LDF)-based models and the chemical kinetic reaction were taken into account to determine the chemical equilibrium of the material. It was observed that the successes of the adsorption refrigerator depend on the source material of the activated carbon and the level of impurity in the activated carbon.

1. Introduction

Otto Mohr was the first man to have the idea of solar refrigerators in 1935; he was the architect and the first to design a working solar refrigerator. Since then so many forms of solar refrigerator have been exposed [1]. A refrigerator that is powered on energy directly obtain from the sun is called a solar refrigerator, and may include photovoltaic or solar thermal energy [2]. A solar-powered refrigerator is a refrigerator, which gets all its energy rate from sunlight. Solar-powered refrigerators has found relevance in recent based on the following: solar-powered refrigerators for solar refrigerators are used to preserve goods especially food from spoilage it also preserve vaccines guy keeping them at a regular temperature [3]; solar refrigerators are used for camping and other recreational event where electricity is no available; when compared to the normal refrigerators solar refrigerators does not have a negative effect to the ozone layer. The shortcoming of the solar-powered refrigerators includes: batteries which must be changed regularly every three years [4]; very heavy set-up that makes mobility difficult; solar refrigerator are very expensive especially the ones that makes use of the batteries.

There are three types of solar refrigerator namely Absorption solar refrigerator, Ranking engine solar refrigerator, and PV (Photovoltaic) solar refrigerator. Absorption solar refrigerator are the least used when compare the to the PV and the mechanical solar refrigerators. This makes use of the absorption cycle to produce the cooling effect of the refrigerator created by the refrigerant (lithium bromide LiBr or silica gel). This solar refrigerator is operated by the principle of heat transfer. Absorption solar refrigerator are categorized into two i.e., liquid refrigerant (lithium bromide) and solid refrigerant (silica gel(H2O and zeolite)). Both refrigerators work on same principle. When the liquid refrigerant passes through the evaporator it evaporates but the solid refrigerant sublime produce the refrigeration effect. When the refrigerant is recycled/ reused it is referred to as closed absorption but if the refrigerant is not reused but ejected then it is called an open absorption.
Adsorption refrigeration has gained wide usability in recent times with increased research on the adsorption refrigeration tubes (ARTs) [5,6]. The general problem of the adsorption refrigerator is its physical configuration, where the ARTs integrated system overcomes the vacuum in a traditional complex adsorption refrigeration system [7]. Based on the above, scientists have been proffering solution using mathematical modelling. Most literatures in modeling studies in adsorption refrigerator have addressed these problems i.e., adsorption performance, heat transfer in the adsorbent bed, and the coupled mass transfer process [8-10]. In this paper, we proposed the importance of structural and material anomalies in the activated carbon as a main challenge that must be modelled.

2. Methodology
The experimental set-up is shown in Figure 1. The linear driving force (LDF)-based models were used to analyse the adsorption performance. The LDF have been used with high accuracies to determine various variables of the ARTs configuration [7, 11].

![Figure 1. Adsorption solar refrigerator system](image)

The LDF is given as:

$$\frac{\partial C}{\partial t} = \frac{15D_o}{R_t^2} \exp \left(-\frac{E_a}{RT_s}\right) \cdot (C_{eq} - C)$$  \hspace{1cm} (1)

$$C_{eq} = C_o \exp \left(-D \left(T_s \ln \frac{P_{sat}}{P}\right)^n\right)$$  \hspace{1cm} (2)

where $C_{eq}$ is the equilibrium concentration at the corresponding pressure and temperature, and $C$ denotes the actual concentration, $\frac{15D_o}{R_t^2}$, $\frac{E_a}{R}$, $C_o$, $D$, $n$ are coefficients obtained from ref [11]. From the laboratory preparation of the activated carbon is characterized with cracks and crevices [12]. Also, the quality of activated carbon depends on the source material [13-14]. Kinetic chemical reaction models according to the reaction order in the differential Equation

$$\frac{dC}{dt} = kC^n$$  \hspace{1cm} (3)

$C$ is the free chlorine concentration in the reactor, $t$ is the contact time, and $k$ is the kinetic constant, $n = 1,2$ or 3. The equation was solved with assumption that: the longer the activated carbon and adsorbed
methanol (liquid state) are in local thermal equilibrium, a chemical reaction is initiated to modify the structure of the activated carbon; the activated carbon is not a pure sample; and the adsorbent bed is packed with uniform-size and isotropic particles.

Table 1. Experimental parameters for adsorption refrigeration [11]

| No | Symbol | Value   | Unit   |
|----|--------|---------|--------|
| 1  | \(n\)  | 1       |        |
| 2  | \(C_o\) | 6.6     | mol/m³ |
| 3  | \(P_{sat}\) | 16.36  | Pa     |
| 4  | \(P\)   | 7140    | Pa     |
| 5  | \(D\)   | 9.08 \times 10^{-6} |        |
| 6  | \(D_o\) | 6.5 \times 10^{-5} | m²/s   |
| 7  | \(R_p\) | 0.055   | m      |
| 8  | \(R\)   | 0.105   | m      |
| 9  | \(T_s\) | 298     | K      |
| 10 | \(k\)  | 0.07    |        |

3. Results and Discussion

The focus of the research is to determine causes of the adsorption rod malfunction via material failure. Equation (3) replaces equation (2) in the LMD model as presented in Equation (1). For the activated carbon and the methanol to function properly, there must be local thermal equilibrium. In this paper, we examined the particulate participation of activated carbon that could sustain this condition. The variables used have been experimentally validated as presented in Table 1. When the kinetic constant of the compound is between 0.01 and 0.09 (Figure 2a), the differential concentration between the activated carbon and methanol is expected to increase linearly. The differential concentration of the compounds at \(k=0.01\) seem to close to the origin. When the kinetic constant is placed between 0.1 and 0.19 (Figure 2b), It was observed that the differential concentration between the activated carbon and methanol had an increased parabolic increase which was more visible at \(k=0.19\). The kinetic constant was further increased between 0.2 and 0.29 to investigate the chemical equilibrium required for the activated carbon to sustain the adsorption performance as presented in Figure 2c. It was observed that the chemical equilibrium was obtained when the kinetic constant is 0.2. However, when \(k=0.29\), the differential concentration increased in parabolic pattern. This result simply means that chemical equilibrium is not dependent on the value of the kinetic constant.
The kinetic constant was examined between 0.3 and 0.39 (Figure 2d). It was observed that chemical equilibrium was attained at k=0.35 and k=0.39. However, at k=0.3, the differential concentration has a parabolic patterned that increased significantly compared to when k=0.29 and k=0.19. When the activated carbon operates at this kinetic constant, the increased differential concentration suggests possible adsorption failure. Based on the above results, the kinetic constant at three unique points were examined i.e., 0.01, 0.1 and 1 (Figure 2e). It was observed that k=0.1 and k=1 fluctuated away from k=0.01 in opposite direction. This observation further affirms that the determination of chemical equilibrium that would aid high adsorption performance is not dependent on a range of values but a selected value that prove that the adsorption refrigerators performance is determined from the initial production of its basic parts. It was observed at this point that the increase or decrease in temperature under laboratory condition does not significantly influence the chemical equilibrium of the material. This observation clearly supports the law of mass action that states that the rate of a chemical reaction at a constant temperature depends only on the concentrations of the substances that influence the rate. The differential concentration was further observed when the kinetic constant is between 1 and 2 (Figure 2f). It was observed that when k ≥1, the differential concentration decreases significantly to cause material failure.
4. Conclusion
The experimentation has examined the relationship between the rate of a chemical reaction, concentration of its reactants, and the particulate dynamics in the activated carbon. This work accurately determined the three possible kinetic constants that can initiate chemical equilibrium that has been projected to enhance the adsorption performance of the activated carbon. In other words, the success of the adsorption refrigerator is dependent on the initial material used for its construction. In this case, the activated carbon is the main determinant of the sustainability of the adsorption refrigerator. Hence, the successes of the adsorption refrigerator depend on the source material of the activated carbon and the level of impurity in the activated carbon.

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References
[1]. AirEaseLeaks, 2020. Solar Refrigerators: PV Refrigerators, Solar Absorption Refrigerators, and Solar Mechanical Refrigerators. https://aireaseleaks.org/solar-refrigerators
[2]. Chaouachi, B.; Gabsi, S. 2007. Design and Simulation of an Absorption Diffusion Solar Refrigeration Unit, American Journal of Applied Sciences, 4:85-88
[3]. Solar Alliance, 2020. How Does a Solar Refrigerator Work? https://www.solaralliance.org/how-solar-refrigerator-work/
[4]. Anyanwu, E. and Ogueke, N. 2007 Transient Analysis and Performance Predic-tion of a Solid Adsorption Solar Refrigerator. Applied Thermal Engineering, 27: 2514-2523
[5]. Zhao YL, Hu E, Blazewicz A. 2012. A non-uniform pressure and transient boundary condition based dynamic modeling of the adsorption process of an adsorption refrigeration tube. Appl Energy, 90: 280–287.
[6]. Zhao HZ, Zhang M, Liu ZY, Liu YL, Ma XD. 2008. Mechanical and experimental study on freeze proof solar powered adsorption cooling tube using active carbon/methanol working pair. Energy Convers Manage, 49:2434–2438.
[7]. Yongling Zhao, Eric Hu, Antoni Blazewicz, 2012. Dynamic modelling of an activated carbon–methanol adsorption refrigeration tube with considerations of interfacial convection and transient pressure process, Applied Energy, 95: 276–284
[8]. P.K. Bansal and A. Martin, 2000. Comparative study of vapour compression, thermoelectric and absorption refrigerators, International Journal of Energy Research, 24: 93–107
[9]. S. A. M. Said, M. A. I. El-Shaawary, and M. U. Siddiqui, 2012. Alternative designs for a 24-h operating solar-powered absorption refrigeration technology,” International Journal of Refrigeration, 35:. 1967–1977
[10]. G. Yaxiu, W. Yuyuan, and K. Xin, 2008. Experimental research on a new solar pump-free lithium bromide absorption refrigeration system with a second generator,” Solar Energy, 82: 33–42
[11]. Leong KC, Liu Y. 2004. Numerical modeling of combined heat and mass transfer in the adsorbent bed of a zeolite/water cooling system. Appl Therm Eng; 24:2359–74.
[12]. T.Ramesh, N. Rajalakshmi, and K.S.Dhathathreyan, (2015). Activated carbons derived from tamarind seeds for hydrogen storage, Journal of Energy Storage, 4: 89–95
[13]. K. Y. Foo, L. K. Lee, and B. H. Hameed, 2013.Preparation of tamarind fruit seed activated carbon by microwave heating for the adsorptive treatment of landfill leachate: a laboratory column evaluation,” Bioresource Technology, 133: 599–605.
[14]. J. Kong, Q. Yue, L. Huang et al., 2013. Preparation, characterization and evaluation of adsorptive properties of leather waste based activated carbon via physical and chemical activation, Chemical Engineering Journal, 221: 62–71