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(Review Article)

## Overview of Adsorption Cooling System based on Activated Carbon – Alcohol Pair

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The depletion of ozone layers and climate problems have been calling for rapid developments in chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HFCs) free air conditioning and heat pump technologies. Using environmental benign refrigerants such as alcohol in adsorption air-conditioning systems will reduce the production of unwanted ozone depleting substances, whilst activated carbon as adsorbent can achieve higher adsorption capacity and rapid adsorption uptake rates. Additionally, it's also environmental friendly and harmless. From this viewpoint, utilization of activated carbon adsorption system using natural alcohol as refrigerants has been in demand. The researchers put efforts to enhance the performance of adsorption systems by modification in adsorbent properties, optimizing the adsorbers' heat exchanger design, and so on towards making this technology competitive with the available cooling system in the market. The objective of this paper is to review on the past efforts of various kinds of researches and methods used to validate the efficiency and suitability of activated carbon as the adsorbent material, with ethanol/methanol for cooling and refrigerant applications.

Keywords: adsorption, activated carbon, alcohol, cooling

### 1. Introduction

#### 1.1 Background

Adsorption refrigeration/heat pump systems are one of environmentally benign technologies because it will use non-harmful materials and can be driven by low temperature heat source such as solar thermal energy or industrial waste heat. This is one of the major reasons why adsorption refrigeration/heat pump systems were intensively studied around the world during the last several decades. In the present status, silica gel-water pair or zeolite-water pair are used in the commercialized adsorption chillers, but many studies also focused on activated carbon as adsorbent<sup>1)</sup>.

Variety of refrigerants were used with carbon adsorbents, such as ammonia<sup>2)</sup>, ethanol<sup>3)</sup>, methanol<sup>4)</sup>, CO<sub>2</sub><sup>5)</sup>, HFCs<sup>6)</sup>, and recently the adsorption characteristics of ethanol onto activated carbon powder (ACP) has been measured<sup>7)</sup>. The predicted performance of ACP-ethanol pair was promising since the specific cooling power of the ACP-ethanol pair was superior to that of silica gel-water pair<sup>8)</sup>. The coefficient of performance (COP) of the both

pairs was similar although the ACP-ethanol pair required a higher regeneration temperature to achieve the maximum COP against the regeneration temperature.

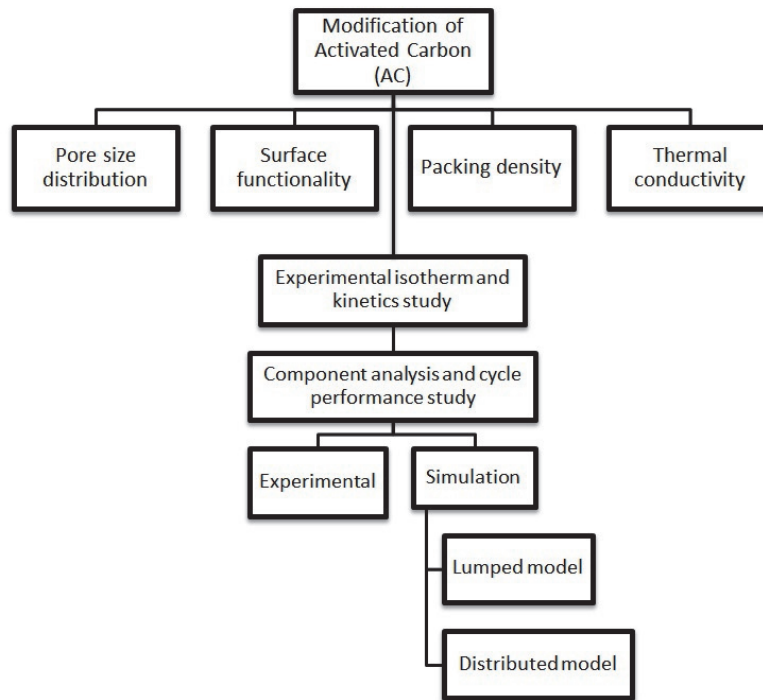
#### 1.2 Alcohol as refrigerants

In adsorption cooling system, working pairs are the most crucial part to be considered. According to Wang et al.<sup>9)</sup>, the refrigerant should exhibit the quality of large latent heat per volume, right freezing point and saturation vapor pressure, good thermal stability and for the same time, the adsorbent should have a good compatibility with refrigerant.

Generally, refrigerants are divided into positive pressure refrigerants and vacuum refrigerants. Both methanol and ethanol, the alcohol refrigerants that were reviewed in this paper are operated at vacuum pressure and these refrigerants are normally used in association with activated carbon or activated carbon fiber. Atan et al.<sup>10)</sup> has listed various of adsorbates for adsorption cooling systems like ammonia, acetone, carbon dioxide, ethanol and methanol, and ethanol was found to be the most

**Table 1**Physical properties of alcohol refrigerants for adsorption systems<sup>9)</sup>.

Alcohol	Chemical formula	Boiling point (°C)	Molar mass (g/mol)	Latent heat of vaporization (kJ/kg)	Density (kg/m <sup>3</sup> )
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	79	46	842	789
Methanol	CH <sub>3</sub> OH	65	36	1102	791

**Fig. 1:** The process involves in adsorption cooling system using activated carbon – alcohol as the adsorbent/refrigerant pair.

favorable for activated carbon fiber (ACF). Table 1 shows some useful physical properties of the alcohol refrigerants. From the properties tabulated in that table, the properties for both of these alcohol adsorbates are almost similar (for the example; ethanol density is 789 kg/m<sup>3</sup> whilst methanol is 791 kg/m<sup>3</sup>), only that ethanol has another advantage which is also a non-toxic refrigerant.

### 1.3 Overview

The authors depicted the 'route' in Figure 1 to visualize the general steps to validate the performance of the activated carbon-alcohol based adsorption cooling system. Starting from the modification of activated carbon properties, the authors reviewed various studies on enhancing the activated carbon properties for various applications. Effectiveness of the activated carbon is dependent on its modification properties to enhance its affinity towards the alcohol adsorbates. The properties

enhancement included in this review are pore size distributions, surface functionality, packing density and thermal conductivity of the activated carbon. The performance of the pairs also discussed by adsorption equilibrium and kinetic study to justify the actual system performance. Finally, both experimental and simulation on the component analysis and the cyclic performance study were reviewed as the final validation before taking the step of commercializing the end products.

## 2. Modification of activated carbon

Activated carbon has been used for many hundreds of years and has now become extremely versatile adsorbent due to its highly developed internal surface area and porosity. Activated carbon with high surface area is widely used in numerous fields, such as fuel gas storage<sup>11)</sup> gas separation<sup>12)</sup>, super capacitor<sup>13)</sup> and catalysis<sup>14)</sup>. The adsorptive properties of carbon are well known long

before the terms active and activated carbon had been developed or coined. The adsorption capacity as one of the most important properties is directly determined by the pore size distribution and is also strongly influenced by the surface functionality<sup>15)</sup>.

It is, therefore, essential to understand the various factors that influence the adsorption capacity of activated carbon prior to their modification so that it can be tailored to their specific physical and chemical attributes to enhance their affinities toward metal, inorganic and/or organic species present in aqueous solutions. These factors include specific surface area, pore-size distribution, pore volume and presence of surface functional groups. Generally, the adsorption capacity increases with specific surface area due to the availability of adsorption site while pore size, and micropore distribution are closely related to the composition of the activated carbon, the type of raw material used, the degree of activation during production stage and the frequency of regeneration<sup>16)</sup>.

## 2.1 Pore size distribution

The shape of the activated carbon affects its pore structure, properties and performance. For example, activated carbon fiber (ACF) mainly possesses micropores and has a rapid adsorption rate and large adsorption amount for small gaseous molecules such as benzene, toluene and butanone<sup>17)</sup>. Activated carbon granules (ACGs) usually have a wider distribution of pore size, from the micropore to the macropore range, and do not exhibit a high adsorption rate. Activated carbon spheres (ACS) have not been studied as much as ACF and ACG, but are expected to possess various advantages over fibers and granules, and to have many applications<sup>18)</sup>.

Yang et al.<sup>19)</sup> has studied three kinds of phenolic resin-based activated carbon spheres with different pore size distributions and was prepared successfully by adding pore-forming agents to a novolac type phenolic resin. The first sample, name as A1 is the phenol-activated carbon sphere (PACS) without additive and exhibits the smallest surface area and mainly micropores. The second sample (A2) is added with polymer blend derived and the mesopores sizes were between 3-5 nm. The third sample (A3) is added with metal blended derived and produced mesopores 3 to 5 nm and macropores 10 to 90 nm. Two type of adsorbates were chosen to characterize the PACS which are creatinine (smaller molecule size, 0.54 nm) and vitamin B12 (molecule size is 2.09 nm). The PACS with the largest specific surface area, A2 gives the largest adsorption capacity for a smaller molecule adsorbate whilst the PACS with largest pore volume, A3 gives the highest adsorption capacity with the larger molecule adsorbate.

Besides that, two types of activated carbon fibers (ACFs) designated as ACC-10 and ACC-15, and one granular activated carbon (GAC) namely F400 have been determined by Lu et al.<sup>20)</sup> and tested on three types of adsorbates namely, phenol, 2-methylphenol and 2-ethylphenol. The molecular structure for these three adsorbates was different where phenol is two-dimensional while 2-methylphenol and 2-ethylphenol are three-dimensional. ACC-10 and ACC-15 have narrow particle size distribution where their critical pore diameters are 8.0Å and 12.8Å respectively while F400 has larger particle size distribution. The study showed that ACFs with narrow particle size distribution are more effective in adsorption as compared to GAC, which has a wide particle size distribution. Other than the particle size distribution, it was found also that the molecule size of adsorbate influences the adsorption capacity. Three-dimensional molecule showed higher percentage increase in adsorptive capacity as compared to the two dimensional molecule phenol for F400 but for ACC-10, phenol provided higher increase in adsorptive capacity as compared to 2-methylphenol.

## 2.2 Surface functionality

Besides the pore structures, the surface functionality also strongly influences the adsorption behavior especially for polar substances such as water and ethanol. The main aim of oxidation of a carbon surface is obtaining a more hydrophilic surface structure with a relatively large number of oxygen-containing surface groups. Table 2 describes some of the textural properties of the surface treated activated carbon.

Kil et al.<sup>21)</sup> investigated the surface functional groups on the adsorption behaviors of the ethanol molecules in carbon micropores using activated carbon (AC) with different amounts of oxygen containing surface functional groups but comparable porosities. Three samples were used in this investigation. The first one is the parent sample; Maxsorb III, the second sample is named as H-MAX where the parent activated carbon was treated with H<sub>2</sub>, by means here with lower contents of oxygen-containing functional groups, and the third sample is named as Ox-MAX, where the parent activated carbon was treated with higher contents of oxygen-containing functional groups, using KOH-activated H<sub>2</sub>. From their study, it was shown that for the activated carbon with an increased amount of surface functional groups, ethanol adsorption/desorption isotherms showed significant decreases in the adsorption amounts and shortened adsorption equilibrium times compared to those with fewer surfaces functional.

**Table 2**

Textural properties of surface treatment activated carbon.

Adsorbent		Maxsorb III	KOH-H <sub>2</sub> - Maxsorb III	H <sub>2</sub> - Maxsorb III	KOH-4R	KOH-6R
<b>Porosity</b>	BET surface area [m <sup>2</sup> /g]	3045	2992	3029	3060	2910
	External surface area [m <sup>2</sup> /g]	-	-	-	20	70
	Total pore volume [cm <sup>3</sup> /g]	-	-	-	1.90	2.53
	Micropore volume [cm <sup>3</sup> /g]	1.7	1.65	1.73	1.85	2.37
	Average pore width [nm]	1.12	1.11	1.15	1.25	1.78
<b>Elemental composition</b>	C [wt.%]	95.13	89.15	97.91	95.37	92.72
	H [wt.%]	0.14	0.27	0.22	0.05	0.10
	N [wt.%]	0.25	0.08	0.12	0.18	0.22
	O <sub>diff</sub> [wt.%]	4.35	10.46	1.75	4.40	5.43
	O/C	0.034	0.088	0.013	0.035	0.044
	Ash [wt.%]	0.13	-	-	-	1.53
<b>Ref</b>		23)	23)	23)	25)	25)

Silvestre-Albero et al.<sup>22)</sup> worked on the adsorption capacity of high porosity and surface area activated carbon onto ethanol. Five samples were prepared using different physical activation period time, i.e., 20, 40, 60 and 72 and 80 hours. They found that the amount of ethanol adsorbed increases with the degree of activation. However, they reported that sample with the 40 hours activation period, provides the highest surface area of 1448 m<sup>2</sup>/g. Therefore, from these findings they concluded that for a low boiling point alcohol such as ethanol there is a critical pore size which allows an optimum packing of the adsorbed ethanol molecules.

The effect of oxidation of activated carbon fibers (ACFs) on the adsorption capacity was examined by Mangun et al.<sup>23)</sup>. The surface treatment applied was both aqueous and non-aqueous treatments and the ACFs applied in their study were designated as ACF-10, ACF-15, and ACF-25. Ammonia and acetone were used to characterize the three types of the ACFs. From this study, it was shown that treatment in the ACF increase the

adsorption capacity significantly. The increment for oxidized fibers with ammonia is up to 30 times compared to untreated ACFs whilst the adsorption capacity of the oxidized fibers for acetone is modestly better than the untreated ACFs.

### 2.3 Packing density

The void volume in the adsorbent reduces the throughput of the thermal adsorber in a manner similar to the clearance volume in a reciprocating compressor. An adsorbent with a higher packing density in the adsorber heat exchanger is a favorable for a maximum performance of the adsorption cooling system.

A method to calculate the minimum packing density necessary for an effective throughput of a thermal compressor was introduced by Akkimiradi et al.<sup>24)</sup>. Three specimens were chosen for comparison namely Fluka, Chemviron and Maxsorb. Maxsorb has the highest surface area and specific adsorption whilst Chemviron has the

highest packing density among all. However, from their calculation method, even though with the highest packing density achieve, still half of the adsorbate amount remain in the void space. They concluded that the adsorbent should not only have a high surface area but also be amenable to achieving a high packing density. Therefore, they recommended that it is important to find a method to reduce the retention void to be less than 20%.

A method to minimize the useless voids (meso, macro and interparticle space), where methane and also alcohol adsorption does not takes place, while maintaining a high micropore volume has been introduced by Lozano-Castello et al.<sup>25)</sup>. They prepared activated carbon monoliths using the parent activated carbon and six different binders, namely as humic acid-derived sodium salt (HAS), polyvinyl alcohol (PVA), Waterlink Sutcliffe Carbons (WSC), novolac phenolic resin (PR), Teflon (TF) and adhesive cellulose-based binder (ADH) to reduce the interparticle void and maximizing the bulk density. Generally, most of the binders used for this purpose reduce the adsorption performance of the activated carbon because they block the micro pores. Based on the pore texture characterization, they analyzed that PR, TF, ADH and WSC are the binders which produce the least micropore blocking.

## 2.4 Thermal conductivity

Activated carbon (AC) is a type of widely utilized physical adsorbent with the advantages of high mass transfer performance, stable adsorption performance, and no corrosion to the metallic part of the heat exchanger, comparing with the chemical adsorbents such as chlorides<sup>26)</sup>. However, it has disadvantage of poor heat transfer performance<sup>27)</sup>, which will lead to low refrigeration efficiency for the reason of long cycle time it required.

Jin et al.<sup>28)</sup> investigated the thermal conductivity and the permeability of three type of activated carbon namely, granular activated carbon, consolidated activated carbon with chemical binder and consolidated activated carbon with extended natural graphite (ENG). Results show that the granular activated carbon and consolidated activated carbon with chemical binder adsorbents have better permeability performance than consolidated activated carbon and extended natural graphite composite adsorbents. However, the consolidated activated carbon with extended natural graphite shows that the best heat transfer performance and their thermal conductivity vary from 2.08 W/m·K to 2.61 W/m·K. Thermal conductivity of granular activated carbon with different sizes almost maintains a constant at 0.36 W/m·K while the value modestly increases to 0.40 W/m·K for the consolidated activated carbon with chemical binder. Therefore, from their findings, they concluded that the consolidated activated carbon with chemical binder is an optimal

choice because it has higher thermal conductivity than granular activated carbon and similar permeability with granular activated carbon.

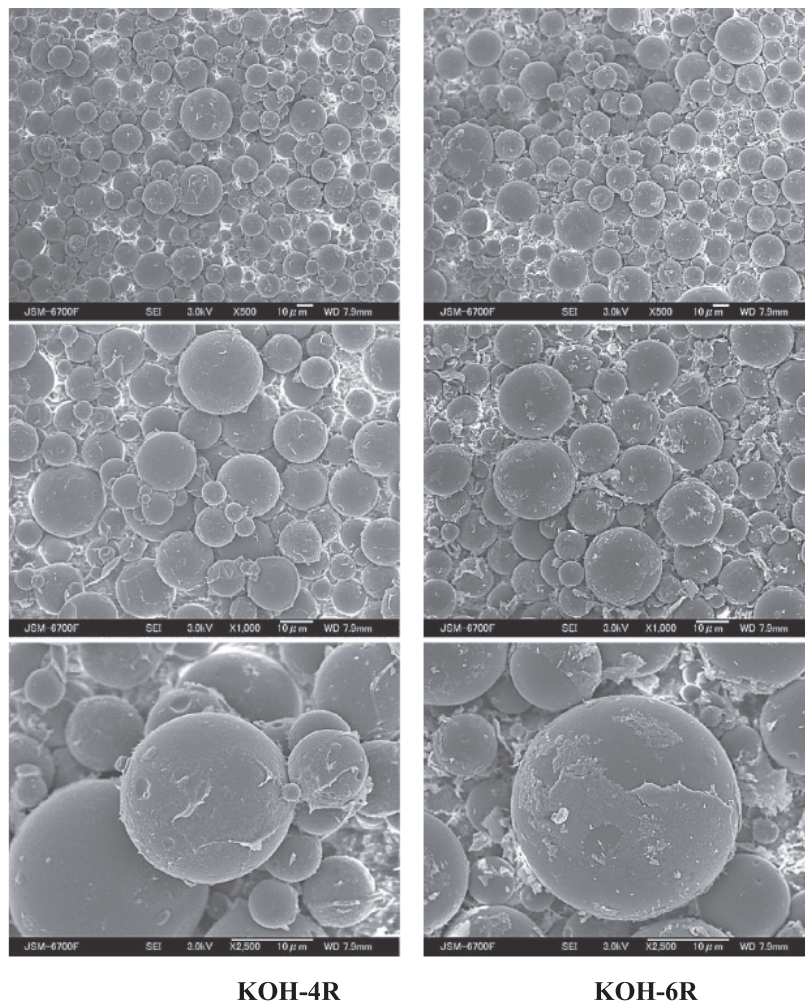
Composite adsorbents, comprising activated carbon and expanded natural graphite have been developed by Wang et al.<sup>29)</sup>. For this particular investigation, they focused on the activated carbon thermal conductivity, permeability and adsorption performance. Results show that the thermal conductivity increased when the ratio of expanded natural graphite in the adsorbent increased, whereas the density of activated carbon decreased when the ratio of expanded natural graphite in the adsorbent increased. However, the highest permeability goes to the simplest solidified adsorbent.

## 3. Adsorbent-adsorbate pair isotherm study

The first step to define the potential of the adsorbent-refrigerant pair in the actual application is by the isotherm study. The adsorption itself describes through isotherm, by means, the amount of adsorbate on the adsorbent as a function of its gas phase pressure at a constant temperature. From the isotherm study, the capacity of the adsorbent to adsorb the adsorbate is identified. Several of activated carbon whether from original component or treated, was produced to fulfill the need.

Adsorption equilibrium uptake of ethanol onto a highly porous activated carbon based adsorbent, namely Maxsorb III, has been experimentally investigated by El-Sharkawy et al.<sup>30)</sup>. Based on the experimental data of equilibrium uptake, P–T–W diagram of Maxsorb III–ethanol pair is plotted. The experimental results show that Maxsorb III can adsorb up to 1.2 kg of ethanol per kilogram of adsorbent and from the theoretical calculations, it was shown that Maxsorb III-ethanol adsorption cycle can achieve a specific cooling effect around 420 kJ/kg at 80°C heat source temperature. Therefore, they recommended thus pair is suitable for the solar applications.

Previously, El-Sharkawy et al.<sup>31)</sup> have investigated adsorption characteristics of ACFs/ethanol pairs for cooling system application. The ACFs used were A-20 and A-15, where both of the ACFs have larger surface area, but A-20 has higher total pore volume. It was found that ACF (A-20)/ethanol pair has considerably higher adsorption capacity, 0.65 kg/kg than ACF (A-15)/ethanol pair, 0.45 kg/kg. Employing ACF (A-20), the effect of the adsorbent apparent density on the adsorption rate was investigated and it is concluded the high apparent density improves the adsorption capacity per unit volume of the adsorber.



**Fig. 2:** SEM pictures of KOH4-PR and KOH6-PR adsorbent samples<sup>23)</sup>.

Recent study by the same authors<sup>32)</sup>, is a new breakthrough of the activated carbon as the adsorbent and ethanol as adsorbate. They claimed that the adsorption uptakes of ethanol onto the two studied spherical phenol resin based adsorbents are significantly higher than adsorption capacity of ethanol onto any other adsorbent. The authors investigated two new adsorbent namely KOH-4R and KOH-6R (as shown at Figure 2), which are the spherical phenol resin treated with different mass and ratios of KOH. From the experimental measurement, they found out that 1 kg of KOH-4R can adsorb 1.43 kg/kg ethanol whilst the KOH-6R can adsorb as high as 2.0 kg/kg.

#### 4. Component analysis and cycle performance study

Continuing from isotherm study, the final validation of adsorbent refrigerant performance is to perform the

adsorbent-refrigerant component analysis and cycle performance test. This set of test mainly consists of the adsorber/desorber, evaporator, condenser and heat source such as solar panel<sup>33)</sup>, exhaust gas<sup>34)</sup> or electric heater<sup>35)</sup>. This cycle conditions could be investigated whether by simulation or experimental study. Table 3 illustrates the performance of the activated carbon-alcohol adsorption cooling systems based on the distributed model simulation and experimental for over the years.

#### 4.1 Simulation

##### 4.1.1 Lumped model

ACF A-20-ethanol pair has been studied by Saha et al.<sup>36)</sup> using transient model for a two bed adsorption chiller. The Dubinin-Raduskevich (D-R) equation is applied to measure the equilibrium uptake and linear driving force (LDF) equation was used to determine the adsorption kinetics. They continued the study with the performance evaluation<sup>37)</sup> by solving the mass balance equation and

**Table 3**

Some recent research studies on activated carbon-alcohol pairs in component analysis and cycle performance test.

Adsorbent-adsorbate pair	System parameters	System performance	Remarks	Ref
<b>Granular palm activated carbon-methanol</b>	Desorption temperature/Adsorption temperature/Mass of adsorbent : 120 °C/40°C/800 g	COP: 0.19 SCP: 396.6 W/kg	Cycle experiment	38)
<b>Granular palm activated carbon-methanol</b>	Desorption temperature/Adsorption temperature/Mass of adsorbent : 90°C/40°C/800 g	COP: 0.27 SCP: 324.78 W/kg	CFD simulation	39)
<b>Solidified activated carbon-methanol</b>	Desorption temperature /Mass of adsorbent : 110°C/60 kg	COP: 0.125 SCP: 16 W/kg	Cycle experiment	40)
<b>Granular palm activated carbon-methanol</b>	Desorption temperature /Mass of adsorbent : 110°C/60 kg	COP: 0.104 SCP: 13.1 W/kg	Cycle experiment	40)
<b>Carbon fiber-ethanol</b>	Desorption temperature/Adsorption temperature/Mass of adsorbent : 100°C/30°C/800 g	the adsorption/desorption cycle time should be short (typically below 300 seconds) in order to attain higher performance	Cycle experiment	41)
<b>Activated carbon powder-ethanol</b>	Desorption temperature/Adsorption temperature/Mass of adsorbent : 90°C/30°C/ 120 g	COP: 0.2 SCP: 358.3 W/kg	Cycle experiment	42)

heat balance equation for the whole system. For evaporator, condenser and adsorber, the simulation was solved using the mass balance equation and energy balance equation. The lumped approach for the adsorption bed, which comprises the activated carbon fiber, the heat exchanger fins and tubes, is given by:

$$(MC_P)_{eff}^{bed} \frac{dT_d^{bed}}{dt} + [mC_P]_{i-phase} \frac{dT_d^{bed}}{dt} = \phi M_{acf} \left( \frac{dw_d^{bed}}{dt} \right) (\Delta H_{st}) - (\dot{m}C_P)_f (T_{f,o} - T_{f,in}) \quad (1)$$

From their simulation results, it is stated that the highest COP and cooling effect of this systems at desorption temperature range from 60 to 90°C, were 0.56 and 12.43 kW, respectively. The simulation also shows that cooling capacity values are optimum for adsorption/desorption cycle time at 600 s with a fixed pre-heating or pre-cooling cycle time. Schicktzanz et al.<sup>43)</sup> also describes an energy balance model of an adsorption chiller to evaluate the performance of activated carbon-methanol heat driven chiller. This is the continuation of the same adsorbent-refrigerant pairs in experimental isotherm study<sup>44)</sup> they were carried before. In their simulation study, they imply that the heat and mass transfer resistances are neglected and the efficiency of the adsorbent is assumed to be 100%. The results show that at desorption temperature range from 85 to 145°C, the highest COP simulated was 0.28.

They also discussed that the COP can be calculated with set of characteristic data which include the operating conditions in terms of temperatures and heat recovery efficiency, the heat exchanger design of the adsorber and the material properties of the working pair used.

#### 4.1.2 Distributed model

Ramji et al.<sup>39)</sup> evaluated the effect of adsorber's wall thickness on the desorption temperature and cooling performance of the ACP-methanol pair employing computer fluids dynamic (CFD) as the simulation technique. This study was also carried out to validate their experimental studies employing the same adsorbent-alcohol pairs<sup>38)</sup>. In this simulation, fluid flow modeling reported by Rybak et al.<sup>45)</sup> had been utilize to solve the classic Navier–Stokes equations by superimposing thousands of grid cells which described the physical geometry of the air flow and heat transfer:

$$\frac{d}{dt}(\rho\phi) + \nabla(\rho v\phi - \psi^{\phi}\nabla\phi) = S\phi \quad (2)$$

The transport equations for mass conservation momentum and energy for any system have been reported by Abdullah et al.<sup>46)</sup>. The simultaneous equations are solved iteratively for each one of the cells to produce a solution which satisfied the conservation law of mass, momentum and energy.

Continuity:

$$\frac{d\rho}{dt} + \frac{d(\rho u_i)}{dx_i} = 0 \quad (3)$$

Momentum:

$$\frac{d(\rho v_i)}{dt} + \frac{d(\rho v_i v_j)}{dx_i} = -\frac{dP}{dt} + \frac{d\tau_{ij}}{dx_i} \quad (4)$$

Energy:

$$\frac{d}{dt}(\rho c_p T) + \frac{d}{dx_i}(\rho c_p T v_i) = \frac{d}{dx_i}\left(k \frac{dT}{dx_i}\right) + \frac{dp}{dt} + \frac{dp}{dx_i} \quad (5)$$

As the results, they found that CFD simulation results agree well with the experimental data. At 120°C desorption temperature and 20 mm adsorber wall thickness, the cooling power and COP achieved were 0.52 kW and 0.27, respectively. The simulation also proves that an optimal wall thickness around 20-30 mm would offer lower heat transfer rate in order to maintain the systems under designated desorption temperature.

## 4.2 Cyclic experimental study

Wang et al.<sup>40)</sup> discussed the performance of activated carbon-methanol adsorption systems concerning heat and mass transfer. Three types of adsorber were analyzed and categorized based on size and shape, and namely as adsorber 1, adsorber 2, and adsorber 3. Besides that, two types of activated carbon namely granular and solidified were also compared. Solidified bed gives the highest heat transfer performance and the adsorber with optimize refrigerant flow channel design gives the best performance among the three. The highest COP and specific cooling power (SCP) achieved were 0.125 and 16 W/kg, respectively at 56 minute's cycle time and 120°C desorption temperature.

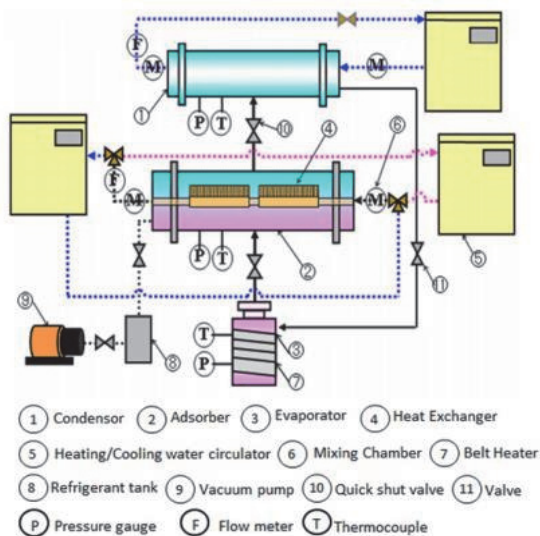


Fig. 3: Schematic diagram of the intermittent ACF/ethanol adsorption refrigeration<sup>41)</sup>.

Saha et al.<sup>41)</sup> has investigated the performance of ACF-ethanol pair experimentally. The test rigs (as shown in Figure 3), for the experiment consist of plate fin heat exchanger adsorber, an evaporator and a condenser. ACF (A-20) fibers are packed tightly inside the fins and are covered by carbon fiber based fine mesh net. The results shown that no temperature differences between the hot water inlet, adsorbent bed, and fin top temperatures after the first ten minutes of the preheating cycle. They concluded that the plate-fin reactor using ACF/ethanol as an adsorbent/refrigerant pair seems to be suitable for adsorption cooling application, however it is desirable to design a lightweight adsorber/desorber heat exchanger to reduce sensible heat transfer losses and also for mobile applications.

Leo et al.<sup>38)</sup> has been built, commissioned and tested prototype of exhaust heat-driven adsorption air-conditioning system using palm-derived activated carbon-methanol. From the experimental results, they listed that by having a cycle time of 20 minutes, an average chilled-air temperature of around 22.6°C is achieved when the cooling coil temperatures fell between 9.5°C to 14.7°C. The COP and SCP of this prototype are approximately 0.19 and 396.6 W/kg. They also pointed out that it is a need to further enhance the efficiency and the associated control system for effective on-the-road application.

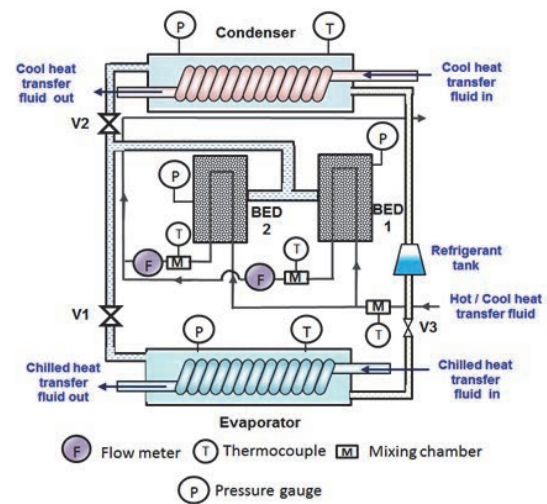


Fig. 4: Experimental set-up of the ACP-ethanol adsorption cooling system<sup>42)</sup>.

The present authors<sup>42)</sup> validated the performance of activated carbon powder (ACP)-ethanol as the adsorbent-refrigerant pair in a two-bed (operated as one bed-like) adsorption cooling cycle as depicted in Fig. 4. The material use as the heat exchanger is aluminum as the target is to apply a lightweight adsorber. With the total amount of ACP packed inside the adsorbers heat exchanger is 0.12 kg, the highest COP achieved was 0.2 at 90°C desorption temperature and 25°C chilled water

temperature. They recommended a new type of activated carbon, which should have higher durability and if possible in a solid form should be developed to suit the heat exchanger application in adsorber.

## 5. Concluding remarks

This paper describes a basic background and “route” on the development of adsorption cooling system employing activated carbon as the adsorbent and alcohol as the refrigerant. From the preliminary studies, various methods and procedures can be applied to enhance the activated carbon properties. In order to get the optimized properties of the adsorbent, some of the constraints have to be minimized without affecting the whole performance of the adsorbent. As for the current conditions, isotherm and lumped model simulation present a very favorable output. From the reviewed studies, the authors have pointed out a promising activated carbon, namely KOH-6R has the highest adsorption capacity with ethanol.

Nevertheless, from the distributed simulation and experimental studies based on the cyclic performance and component analysis, hundreds of rooms’ improvements to be made in order to ensure that activated carbon are the right adsorbent material and also to ensure that the adsorption cooling technology is competitive one. The practical challenge now is the durability of the activated carbon itself when it is packed inside the adsorber/desorber heat exchanger. We believe that, reproducing the powder in a solidified form and at the same time retaining or maybe even better enhancing the carbon textures and thermodynamic properties as the adsorbent should be done to ensure the activated carbon is a realistic material to be applied in the commercial adsorption cooling.

## Nomenclature

### Symbols

$C_p$	specific heat capacity (J/kg.K )
$M$	mass (kg)
$m$	mass (kg)
$\dot{m}$	mass flow rate (kg/s )
$T$	temperature (K)
$\Delta H_{st}$	isosteric heat of adsorption (J/kg )
$v_i$	velocity (m/s )
$P$	pressure (N/m <sup>2</sup> )
$k$	thermal conductivity (W/m.K)
$t$	time (s)

### Subscripts

$acf$	activated carbon fiber (ACF)
$eff$	effective
$d$	adsorption or desorption
$in$	inlet
$f$	cooling source or heating source
$o$	outlet

$v$	vapor
$w$	water
$i$	$i$ -direction
$j$	$j$ -direction
$k$	$k$ -direction

### Superscripts

$bed$	sorption heat exchanger
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### Greek symbols

$\psi$	exchange coefficient
$\tau_{ij}$	stress tensor
$S\phi$	source/sink term
$\rho$	density (kgm <sup>-3</sup> )

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