COMPARATIVE STUDY OF THREE DIFFERENT ADSORBENT-ADSORBATE WORKING PAIRS FOR A WASTE HEAT DRIVEN ADSORPTION AIR CONDITIONING SYSTEM BASED ON SIMULATION

H. R. Ramji, 2S. L. Leo, 1I. A. W. Tan & 1M. O. Abdullah
1Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, East Malaysia
2 International College of Advanced Technology Sarawak (ICATS), Jalan Canna, Off Jalan Wan Alwi, Tabuan Jaya, 93350 Kuching, East Malaysia
E-mail: amomar13@gmail.com; amomar@feng.unimas.my

ABSTRACT

In a previous study, a laboratory prototype of a thermal-driven adsorption air conditioning system employing activated carbon as adsorbent and methanol as the refrigerant was successfully developed. The experimental results employing the prototype obtained a COP of 0.19 and cooling capacity $Q$ of around 320 kJ. The cooling power $P$ yielded ~ 0.64 kW and it was able to produce chilled air temperature $T_{chill,out}$ of around 22 °C. In the present study, further works are conducted via simulation to carry out “what-if” analysis viz. to determine the optimal adsorbent-adsorbate working pair based on the prototype. Three types of refrigerants, coupled with activated carbon, were considered in this study, namely (1) methanol (similar to the experimental works); (2) ammonia; and (3) water. The simulation results obtained showed that activated carbon-water pair produced the best cooling compared to activated carbon-methanol and activated carbon-ammonia working pairs, as far as present study is concerned. The methanol and ammonia showed a COP of 0.37 and 0.4, respectively. The average $T_{chill,out}$ produced by methanol was around 15 °C while the temperature produced by ammonia was slightly higher around 19 °C. The cooling capacity $P$ for methanol and ammonia showed a value of 0.65 kW and 0.50 kW, respectively. Activated carbon-water pair simulated to yield a higher COP of 0.58 with $Q$ at 480 kJ mainly due to high heat of evaporation, which was able to produce average $T_{chill,out}$ of 12 °C with cooling power of approximately 1 kW.

Keywords: Adsorption air conditioning system; Activated carbon; COP; Cooling power; Simulation; Waste heat.

1. INTRODUCTION

The recent European Union directive on mobile air conditioning (MAC) phases out system using HFC-134a as refrigerant on the EU market from 2008 onwards (Reference). This leads to other alternative systems such as adsorption air conditioning system. Air conditioning technology is required to evolve due to the new environmental regulations which are concerning about the depletion of the ozone layer thus causing global warming. As a result, this trend has led to a strong demand for a new air conditioning technology (see e.g., Leo SL, Abdullah MO, 2009 [1]. As far as automobiles are concerned, unfortunately, no working adsorption cooling system has been practically run due to various restrictions - in particular due to sizing and cooling capacity limitations (Abdullah et al, 2011) [2].

There were several prototypes of adsorption refrigeration systems reported in literature, most of which were for ice making industry and others were designed for air conditioning purposes. Wang et al. (2001) [3] have reviewed an adsorption refrigerator driven with a heat source temperature of 100 °C. The refrigerator could obtain specific refrigeration power for 5.2 kg-ice/day per kg adsorbent with SCP of 150 W/kg adsorbent and a COP close to 0.5. In another study done by Wang et al. (2001) [3] on adsorption solar ice maker, 5-7 kg-ice/day per square meter solar collector could be produced continuously in well lighted condition, making use of solar energy.

Meanwhile Tso et al. (2012) [4] had developed a chiller system powered by waste heat employing activated carbon-sodium silicate/calcium chloride. The outcome was chilled water temperature of 9 °C utilizing waste heat temperature of 85 °C as driving source. A COP and SCP of 0.65 and 380 W/kg-adsorbent were obtained respectively in their study. The corresponding adsorption-desorption cycle time of the operation showed that one full cycle could be completed optimally in 360 seconds.

Xia et al. (2009) [5] had performed an analysis on an adsorption chiller employing silica gel-water pair with a methanol evaporator for cooling purposes. They obtained a COP of 0.39 with the heat source temperature of 82.5 °C, cooling water temperature of 30.4 °C and the temperature of the chilled water produced was 12 °C.

Meanwhile, Sato et al. (1997) [6] had presented a multiple-stage adsorption air conditioning system for vehicles. Although the efficiency of the multiple-stage adsorption system was improved, the size of the system also increased.
and its control system became more complex. Zhang et al. (2000) [7] had described an experimental intermittent adsorption cooling system driven by the waste heat of a diesel engine. Zeolite 13X-water was used as the working pair and a finned double-tube heat exchanger was used as the adsorber. The COP and specific cooling power (SCP) of the system was 0.38 and 25.7 W/kg, respectively. Wang et al. (2001) [8] had studied an adsorption air conditioning for a bus driven by waste heat from exhausted gases. The working pair for this system was activated carbon and ammonia with the cooling power of 2.58 kW and a COP of 0.16. The activated carbon was pressurized to a density of about 900 kg/m$^3$ to fit additional adsorbent into the adsorber. The total weight of the two adsorbers was about 248 kg and occupied about 1.0 m$^2$.

In another research by Lu et al. (2004) [9] it was presented in experimental studies on the practical performance of an adsorption air conditioning system powered by exhaust heat from a diesel locomotive. The system was incorporated with one adsorbent bed and utilized zeolite and water as a working pair to provide chilled water for conditioning the air in the driver’s cab of the locomotive. Their experimental results showed that the adsorption system was technically feasible and could be applied for space air conditioning. Under typical running conditions, the average refrigeration power ranging from 3.0 to 4.2 kW has been obtained. However, this system might not be suitable for automobile application due to its size and high regenerative temperature.

According to Leo and Abdullah (2009) [1] for their research findings on automobile adsorption application, the COP obtained through experimentation was approximately 0.19. Theoretically the value was quite small compared to regular air conditioning available in the market. In spite of this, the value of specific cooling power recorded was a promising 396.6 W/kg. With a cycle time set at 20 minutes, the average chilled air produced was around 22.6 °C. The prototype operated intermittently between two adsorbers in order to retain the chilled air along the 20 °C temperature line. Being able to produce this degree of air conditioning, the cooling coil temperatures could fall to a range of 9.5 °C to 14.7 °C.

Now, this paper is a continuation of study by Leo & Abdullah et al. (2009) [1] and Abdullah et al. (2011) [2] on adsorption cooling system. In previous papers, the authors had discussed the basic prototype design and conducted several relevant experimentation works. In this paper, however, extended simulation works by CFD are presented; ways to achieve better performance and minimize unnecessary energy losses are also discussed herewith. In attaining the specified condition and cooling performance, subsequently, a comparative study was carried out based on three working pairs (utilizing activated carbon as adsorbent) where methanol, ammonia, and water were employed as the adsorbate (or refrigerant) in the adsorption air conditioning system. By varying these different pairs, the corresponding variables such adsorption rate, heat transfers and operating cycle time were obtained. Subsequently, performance parameters such as cooling power, $P$; cooling capacity, $Q$; and COP for all the three working pairs were also modeled, simulated and analyzed.

2. EXPERIMENTAL SYSTEM SETUP AND DESCRIPTIONS

In this laboratory scale settings, a four stroke Subaru Robin 5.0 Hp powered engine was used to supply high temperature fume gas. The exhaust gas produced by this engine could easily reach temperature of minimum 150 °C. The engine was able to release a range of 150 °C – 200 °C of fume gas temperature. This prototype comprised of two identical adsorbers placed side by side, a condenser, an evaporator, and three cooling fans.

The operation of the adsorption air conditioning system is a periodic succession of adsorption and desorption processes. When the adsorbent is heated up in the first adsorber, the refrigerant vapour is desorbed and later condensed in the condenser, and the condensed liquid is then transferred to the evaporator. The refrigerant vapour is readorsorbed by the adsorbent in the second adsorber in the cool down process. The cooling down process is assisted by three cooling fans placed at their designated locations. The schematic diagram of the prototype during operation is given in Figure 1.
In this prototype, the adsorber was designed to intensify the heat and mass transfer of the adsorbent bed and maximize the quantity of activated carbon to be packed. The adsorber had a length of 40 cm, a width of 20 cm and a height of 10 cm. The refrigerant fluid flew through the internal channels of the tubes. A total of 1.6 kg of oil palm shell derived granular activated carbon was packed between the fins of the tubes. The particle size of the activated carbon was <3.0 mm, with surface area of 1000–1100 m²/g, total pore volume of 0.5–0.6 cm³/g, density of 0.431 g/cm³ and iodine number of 1180. The heat of adsorption of the activated carbon was 1800 kJ/kg.

Air finned tube aluminum heat exchangers were used as the condenser and the evaporator. Though for the evaporator a hanging type was chosen to provide better cooling instead. These heat exchangers were attached with a 12V dc fan to increase the heat rejection rate to the surrounding and thus increasing the cooling effect. The evaporator that served as the heat absorption component was used to remove heat from the space and also dehumidification. The moisture contained in the air condensed at the evaporator coil as the warmer air travelled through the coil.

The temperature of the heat exchanging fluid was measured at the entrance and the exit of the condenser and evaporator. The temperatures of the overall system and surrounding area were observed through thermal couples and thermal camera. Along side the temperature, pressures were also measured in the adsorber, condenser and the evaporator.

Figure 2 shows the placement and integration of the components in the prototype, which consists of two adsorbers, a blower, an evaporator attached to two blowers, a condenser attached to a fan, an expansion valve, four check valves, three three-way valves, an engine, and several pipe connectors. The detail design of the complete system was given in the work of (Abdullah and Leo 2008) [10].
This prototype generally worked in two main phases, i.e. desorption phase and adsorption phase. Practically the cooling effect was due to the adsorption process; while desorption on the other hand worked as pre-cooling in the operation as to prepare the adsorbent for the adsorption process. Throughout this process, desorption and adsorption had to work continuously in a suitable time limit which was often referred to as time cycle. Hence, to achieve this condition, an intermittent operation was designed whereby two adsorbers of same design were used. The idea was that whenever one of the adsorber was undergoing adsorption, the second adsorber would undergo desorption. Through this scheme, a continuous cooling could be provided by this system.

3. PHYSICAL AND MATHEMATICAL MODEL

3.1 The adsorber

The Dubinin-Astakhov (D-A) equation that relates the concentration and temperature is represented in the form of (Lu et al. 2004) [9];

\[ x = x_0 \exp \left( -k \left( \frac{T}{T_s} - 1 \right)^n \right) \]  

(1)

Where \( x \), represents the concentration of methanol adsorbed in bed at the temperature of the adsorption, \( T \). \( T_s \) represents the saturated temperature in the adsorber with given pressure, \( P \). The saturated adsorption capacity of the working pair is given by \( x_o \). The parameter \( k \) and \( n \) are constants that vary with different working pair.

3.2 Mass and energy balance equation

3.2.1 Adsorption rate

The adsorption process in this system could be divided into two phases which were desorption (regeneration) phase and also the adsorption phase. In this system, these two identically design adsorbers would be operating intermittently with each other. The cycle time would rely heavily on the adsorption and desorption rate of the system as given in the equations by Tso et al. (2012) [4]:

\[ \frac{dx_{ads}}{dt} = K_{ads} (x_{ads,eq} - x_{ads}) \]  

(2)

\[ x_{ads} = x_{ads,eq} - (x_{ads,eq} - x_{ads,o}) \exp(-K_{ads}t) \]  

(3)

\[ \frac{dx_{des}}{dt} = K_{des} (x_{des}) \]  

(4)

\[ x_{des} = x_{des,eq} - (x_{des,eq} - x_{des,o}) \exp(-K_{des}t) \]  

(5)

3.2.2 Condenser and evaporator model

In modeling the condenser and evaporator, several assumptions have been considered as following.

1. The working fluid was considered always in thermodynamic equilibrium corresponding to its saturation conditions.
2. The saturated temperature depended on the internal pressure of the working equipments given by Antoine equation with parameter as shown in Table 1 [11].
3. The refrigerant contained inside the adsorbent was completely desorbed before shifting to adsorption phase.
4. the entire refrigerant fluid flow rate coming from the condenser was instantly evaporated. There would be no fluid lost in between the processes. Every amount of refrigerant desorbed in the first adsorber would be transferred in completion to the next adsorber where adsorption took place.

This means;

\[ m_{ref} = x_{des} m_{ac} \]  

(6)
### Table 1. Antoine equation for given refrigerants

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Temperature range (°C)</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>(-20-140)</td>
<td>7.87863</td>
<td>1473.11</td>
<td>230</td>
</tr>
<tr>
<td>Ammonia</td>
<td>(-83-60)</td>
<td>7.55466</td>
<td>1002.711</td>
<td>247.885</td>
</tr>
<tr>
<td>Water</td>
<td>(0-150)</td>
<td>7.96681</td>
<td>1668.21</td>
<td>228</td>
</tr>
</tbody>
</table>

While employing the usual energy equation, the total heat power input to the system including the condenser and evaporator models can be presented as below:

**Total heat power input**

\[ P = m_{eg} C_{p,eg} (T_{eg,in} - T_{eg,out}) \]  

(7)

**Condenser**

\[ m_{ref} c_{p,ref} (T_{des} - T_{cond}) + h_{v,ref} = m_{air} c_{p,air} (T_{out} - T_{in}) \]  

(8)

**Evaporator**

\[ h_{v,ref} - m_{ref} c_{p,ref} (T_{cond} - T_{ev}) = m_{air} c_{p,air} (T_{in} - T_{out}) \]  

(9)

### 3.3 System performance parameters

#### 3.3.1 Cooling power and cooling capacity

The cooling output readings of the prototype via experiment were calculated from measuring the temperature difference of the inlet and outlet of the chilled air by its flow rate and specific heat (Lu et al. 2004) [9]:

\[ P_{exp} = m_{chill} c_{p,air} (T_{chill,in} - T_{chill,out}) \]  

(10)

The total cooling capacity would be:

\[ Q_{c,exp} = \int P_{exp} dt \]  

(11)

While in simulation, cooling power could be obtained theoretically by:

\[ Q_{c,tho} = m_{ref} \left( q_{v,ref} - c_{p,ref} (T_{cond} - T_{ev}) \right) \]  

(12)

Hence, the total cooling capacity could be presented as;

\[ P_{tho} = \frac{m_{ref}}{t_{cycl/2}} \left( q_{v,ref} - c_{p,ref} (T_{cond} - T_{ev}) \right) \]  

(13)

Where \( q_{v,ref} \) is the heat of evaporation for methanol, and \( t_{cycl/2} \) is the half cycle time of the whole operation.

#### 3.3.2 Coefficient of performance (COP) and specific cooling power (SCP)

The performance of the adsorption cooling system is commonly evaluated using two performance factors; the coefficient of performance (COP) and specific cooling power (SCP). In general, COP is the amount of cooling produced by an adsorption cooling system per unit heat supplied [9] as shown:

\[ COP = \frac{Q_{ev}}{Q_{in}} \]  

(14)

The SCP, on the other hand, is defined as the ratio between the cooling production and the cycle time per unit of adsorbent weight, as given below [1]:

\[ SCP = \frac{Q_{ev}}{m_{ac}} \]  

(15)

Since SCP relates to both the mass of adsorbent and the cooling power, it reflects the size of the system. For a nominal cooling load, higher SCP values indicate the compactness of the system.
3.4 Governing equations
In simulation, fluid flow modeling described by Siegal and Howel (1992) [12] had been utilized to solve the classic Navier-Stokes equations by superimposing thousands of grid cells which describe the physical geometry of the air flow and heat transfer, ie:

\[
\frac{\partial}{\partial t}(\rho \phi) + \nabla \left( \rho \mathbf{v} \phi - \mathbf{v} \cdot \nabla \phi \right) = S \phi
\]  

(16)

The transport equations for mass conservation, momentum and energy for any system are given in these generic equations (Siegal and Howel (1992) [12], Abdullah et al. (2006) [13]:

**Continuity:**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \mathbf{v}_i)}{\partial x_i} = 0
\]  

(17)

**Momentum:**

\[
\frac{\partial (\rho \mathbf{v}_i)}{\partial t} + \frac{\partial (\rho \mathbf{v}_i \mathbf{v}_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i}
\]  

(18)

**Energy:**

\[
\frac{\partial (\rho c_p T)}{\partial t} + \frac{\partial (\rho c_p T \mathbf{v}_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( k \frac{d T}{d x_i} \right) + \frac{dP}{dt} + \frac{dp}{dx_i}
\]  

(19)

The simultaneous equations were solved iteratively for each one of the cells to produce a solution which satisfied the conservation law of mass, momentum and energy.

In a previous study, we had considered double adsorber prototype design and reported the associated simulation works [16]; while in the current study, a three different adsorber/adsorbent working pairs were being investigated.

4. SIMULATION RESULTS AND ANALYSIS
During the heating process, refrigerant was desorbed and pressurized from the adsorber. Simultaneously, the adsorber was initially prepared to contain 45 %, 26 % and 29 % of methanol, ammonia and water, respectively (in accordance to Eq.(1)). Theoretically, the more refrigerant were desorbed, the more cooling effect could be produced. Equivalently, the ability of refrigerant to be squeezed out of the adsorbent bed would indicate the effectiveness of the heat transfer processes of the system.

In Fig. 3 (a), the diagram illustrates the early condition of the adsorber when the activated carbon and refrigerant were at room temperature around 30 °C. Once the exhaust gas had entered the area, the heat of the exhaust gas vaporized the refrigerant within the activated carbon. The pressurized refrigerant would be released from the adsorber due to pressure difference, thus making its way to the evaporator. In this condition the adsorber was in desorption process. While in Fig. 3 (b), the adsorption process took place at the same time but on the second adsorber desorption took place. The diagram shows that the source of heat was from the refrigerant and activated carbon side. This heat was transferred to the cool air blown by the blower to hasten the cool down process.
The ratio between adsorbate and adsorbent in this system was set according to Eq. (1) provide. It was to be noted that an excess amount of adsorbate could cause over saturation of activated carbon that could lead to reduction of system performance (e.g. see Leo and Abdullah, 2009) [1].

4.1 Adsorption isobar
In Fig. 4 the adsorption isobars for the respective working pairs are presented. The saturated temperature, \( T_s \) used were corresponding to the saturated pressure, \( P_s \) that were utilized in experimental works by Leo and Abdullah (2009) [1]. In this result \( T_s \) implemented was 45 °C. This indicated that the operating pressure of the adsorber would depend on the adsorbate used. The saturated pressure \( P_s \) was 0.09, 0.5 and 18 bar for activated carbon-methanol, activated carbon-water and activated carbon-ammonia pair, respectively. The parameters for the DA-equation for each of the working pairs are given in Table 2 [14].

Fig. 3 Simplified (a) desorption and; (b) adsorption mechanism that occurs inside the adsorber. The circles represent the activated carbon granular. The shaded region indicates the refrigerant.

Fig. 4 Adsorption isobar capacity for respective working pair (ac= activated carbon)
Table 2 D-A equation constant values for appointed working pair [13]

<table>
<thead>
<tr>
<th>Working pair</th>
<th>k</th>
<th>( x_0 )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated carbon - methanol</td>
<td>13.38</td>
<td>0.45</td>
<td>1.5</td>
</tr>
<tr>
<td>Activated carbon - ammonia</td>
<td>3.57</td>
<td>0.29</td>
<td>1.38</td>
</tr>
<tr>
<td>Activated carbon - water</td>
<td>5.36</td>
<td>0.26</td>
<td>1.73</td>
</tr>
</tbody>
</table>

4.2 Adsorbate concentration, \( x_{des} \) against time, \( t \).

The graphs in Fig. 5 were plotted to show the relationship of refrigerant concentration in the adsorber, \( x_{des} \) during desorption phase against time, \( t \). In this particular simulation setting, a constant exhaust gas inlet temperature, \( T_{eg,in} \) of 200 °C was used as the heat energy source. Desorption temperature; \( T_{des} \) was identified to be below 150 °C throughout the process for all the working pairs.

![Fig. 5](image)

**Fig. 5** Concentration of refrigerant during desorption phase, \( x_{des} \) against time, \( t \) for respective working pair \( (T_{eg,in} = 200 \degree C) \)

The results showed that activated carbon-ammonia working pair had the shortest desorption time (around 420 sec) followed by water (480 sec) and methanol (600 sec). This could be explained by the volatility of the refrigerant used. In comparison, ammonia was the most volatile compound used then methanol and water when arranged in decreasing volatility. Methanol took longer time than water to be desorbed because of greater initial concentration, \( x_0 \) in the adsorber.

4.3 Influence of evaporating temperature, \( T_ev \) on chill temperature release, \( T_{chill,out} \) and COP

Fig. 6 shows the simulated chilled temperature release, \( T_{chill,out} \) and COP of the system at different evaporating temperatures, \( T_{ev} \). According to Fig. 6, \( T_{chill,out} \) was lower at higher \( T_{ev} \) and it applied to all the refrigerants used. In this graph, it shows that activated carbon-water working pair produced the lowest \( T_{chill,out} \) in the range of 12 to 13°C. This was followed by methanol and ammonia that achieved \( T_{chill,out} \) of 15 to 17°C and 18 to 20°C, respectively. This implied that activated carbon-water provided the best cooling profile. The results obtained were based on the evaporator parameters given in Table 3.
Fig. 6 Influence of evaporator temperature, $T_{ev}$ on chilled temperature release, $T_{chill,out}$ and coefficient of performance for the system, COP.

Table 3 Evaporator parameters

<table>
<thead>
<tr>
<th>$T_{chill,in}$</th>
<th>$C_p, air$</th>
<th>$m_{air}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°C</td>
<td>1.005kJ/kg°C</td>
<td>0.045kg/s</td>
</tr>
</tbody>
</table>

Fig. 6 also shows the effect of $T_{ev}$ on the system COP. The graph indicated that when the $T_{ev}$ was increased, the COP of the system would slightly increase as well. COP of the adsorber depended greatly on the cooling capacity, $Q$ and also the cycle time, $t_{cyc}$ of the operation. Based on the graph, activated carbon-water pair yielded the highest COP of 0.58. This working pair also exhibited only slight changes to COP as a function of $T_{ev}$. Simultaneously, activated carbon-ammonia pair had a COP of around 0.4 while activated carbon-methanol pair yielded slightly lower COP value of 0.37.

4.4 Influence of evaporating temperature, $T_{ev}$ on cooling power, $P$ and cooling capacity, $Q$.

The simulated cooling power, $P$ and cooling capacity, $Q$ with the influence of evaporator temperature, $T_{ev}$ is shown in Fig. 7. The graph depicted that when $T_{ev}$ was low, cooling power and cooling capacity were low as well. These two parameters were directly proportional to the $T_{ev}$ of the system. In the results obtained from the simulation, activated carbon-water pair produced the highest $P$ and $Q$ of nearly 1 kW and 480 kJ, respectively. These results showed coherency towards the data obtained for $T_{chill,out}$ and COP. The lowest $P$ is obtained from activated carbon-ammonia pair that yields only around 0.7 kW and $Q$ in the range of 280 to 300 kJ. Activated carbon-methanol pair exhibited a nearly equivalent $Q$ but showed higher value of $P$ that was around 0.8 kW. The difference was due to the effect of cycle time, $t_{cyc}$ taken in getting $P$ values. By using ammonia as refrigerant, the cycle time was shorter than of methanol as shown in Fig. 5 and discussed in section 4.2. From the gradient of the graph, it was also shown that activated carbon-methanol had the greatest effect to the changes of $T_{ev}$. 
Fig. 7 Influence of evaporator temperature, $T_{ev}$, on cooling power, $P$ and cooling capacity, $Q$.

4.5 Chilled temperature released, $T_{chill,out}$, and cooling power, $P$, of the adsorber against time, $t$

Fig. 8 shows the plot of chilled temperature released, $T_{chill,out}$, by the evaporator as a function of time, $t$. The graph depicted that in comparison of the three refrigerants used, water was able to produce the lowest $T_{chill,out}$. It was considered here that lower $T_{chill,out}$ was more favorable in this system. By using water as refrigerant, $T_{chill,out}$ produced could be down to 12°C whereas methanol and ammonia could produce $T_{chill,out}$ around 15 °C and 19 °C, respectively.

Fig. 8 Chilled temperature release, $T_{chill,out}$, by the evaporator against time, $t$ for respective working pair.

In Fig. 9, the simulated cooling power, $P$, of each working pair is plotted against time, $t$. It was in coherence with the results shown in Fig. 8, in which activated carbon-water exhibited the highest $P$ of up to 0.80 kW. It was followed by activated carbon-methanol pair that produced $P$ at around 0.65 kW and activated carbon-ammonia pair at 0.50 kW. Based on the results shown in both Figs 8 and 9, it could be concluded that this was due to the different values in the heat of vaporization of the refrigerant, $H_v$. In comparison, water possessed the highest $H_v$ followed by methanol and ammonia.
5. DISCUSSIONS

In the adsorption refrigeration system, working pairs are the most crucial part to be considered. According to Wang et al. (2010) [15] explaining the basic principle and working characteristics of the adsorption refrigeration system, the adsorbent should have the characteristics of:

1. large adsorption capacity
2. large change of adsorption capacity with temperature variation
3. flat desorption isotherm
4. good compatibility with refrigerant

Similarly in vapor compression refrigeration system, refrigerant should exhibit the quality of:

1. large latent heat per volume
2. right freezing point and saturation vapour pressure
3. good thermal stability

Based on the given criteria, the working pairs for adsorption system were decided. Currently there are no working pairs that completely meet the requirements mentioned. But the commonly used working pairs closely meet these conditions [15]. Therefore, the working pairs such as activated carbon–methanol, activated carbon–ammonia and activated carbon–water were tested in the adsorption system designed by Leo and Abdullah (2009) [1] for real life implementation. After careful selection of the suitable working pairs guided by the prerequisite as listed in the preceding paragraph extracted from Wang et al. (2010) [15], the performance parameters simulated in the present study are now summarized in Table 4. The results showed that activated carbon–water pair had given the most desirable results with the best cooling in terms of COP, cooling power, cycle time and average chilled temperature.

<table>
<thead>
<tr>
<th>Adsorbent/Refrigerant</th>
<th>Methanol(Exp)</th>
<th>Methanol(Sim)</th>
<th>Ammonia</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of adsorbent, m_{ref} (g)</td>
<td>360</td>
<td>360</td>
<td>230</td>
<td>210</td>
</tr>
<tr>
<td>Cycle time, t_{cyc} (s)</td>
<td>1200</td>
<td>1200</td>
<td>840</td>
<td>960</td>
</tr>
<tr>
<td>Average chilled temperature produce, T_{chill, out} (°C)</td>
<td>22</td>
<td>15</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>Cooling power, P (kW)</td>
<td>0.64</td>
<td>0.65</td>
<td>0.50</td>
<td>0.98</td>
</tr>
<tr>
<td>Cooling capacity, Q (kJ)</td>
<td>320</td>
<td>390</td>
<td>210</td>
<td>480</td>
</tr>
<tr>
<td>Coefficient of performance, COP</td>
<td>0.19</td>
<td>0.37</td>
<td>0.40</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Fig. 9 Cooling power, P against time, t for the respective working pair.
6. CONCLUSIONS

Based on the simulation results, it was found that activated carbon-water working pair would be the preferred adsorbent-adsorbate to be utilized in this adsorption air conditioning system. The activated carbon-water pair produced the optimal cooling compared to methanol and ammonia as far as the range of parameters in the study was concerned. The methanol and ammonia showed a COP of 0.37 and 0.4, respectively. $T_{\text{chill, out}}$ produced by methanol was around 15 °C while the value produced by ammonia was slightly higher around 19 °C. The cooling capacity, $P$ for methanol and ammonia showed a value of 0.65 kW and 0.50 kW, respectively. Meanwhile, activated carbon-water pair yielded a COP of 0.58 with $Q$ at 480 kJ. This system was able to produce $T_{\text{chill, out}}$ of 12 °C with cooling power of approximately 1kW.

7. REFERENCES


NOMENCLATURE

$A$  
cross sectional area (m$^2$)

$A_{lm}$  
log mean area

$C_p$  
specific heat capacity (Jkg$^{-1}$K$^{-1}$)

COP  
coefficient of performance

$h$  
convective coefficient

$k$  
constant in Dubinin equation

$m$  
mass (kg)

$P$  
cooling Power (kW)

$Q$  
cooling capacity (kJ)

$q_v$  
vaporization heat

SCP  
specific cooling power

$T$  
temperature (°C)

$t$  
time (s)

$x$  
concentration (kgkg$^{-1}$)

$x_o$  
initial concentration (kgkg$^{-1}$)

Subscript

ac  
activated carbon

ads  
adsorption

cyc1/2  
half cycle

eg  
exhaust gas

exp  
experimental

des  
desorption phase

ev  
evaporator

i  
inside

o  
outside

ref  
refrigerant (methanol)

s  
saturated

v  
vaporization

Superscript

$n$  
constant in Dubinin equation

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