THE PERFORMANCE OF COMMERCIAL ACTIVATED CARBON ABSORBENT FOR ADSORBED NATURAL GAS STORAGE

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ABSTRACT
Storage of natural gas by adsorption or called Adsorbed Natural Gas (ANG) has the potential to replace Compressed Natural Gas (CNG) in mobile storage applications, such as in vehicles. ANG storage at moderate pressure around 3.5 to 4.2 MPa could be expected to reduce the problem of bulky storage within a confined space of high-pressure CNG storage used in vehicle. In adsorptive storage, the amount of gas stored in the vessel is enhanced when a large portion of gas adsorbs on the adsorbent and thus lowering the storage pressure. Commercial activated carbon adsorbent was conducted to determine the storage capacity and delivery performance of the ANG storage. The adsorptive storage test was carried out under dynamic condition to resemble storage behavior during filling and discharging. The 0.5 liter pressurized vessel used to store methane is charged up to 3.5 MPa and then brought down to atmospheric pressure to discharge the stored gas. Both filling and discharging process is done at varied flow rates. The results shown that the ANG storage experienced significant thermal changes during adsorption and desorption of the gas therefore affected the storage performance. The rate of filling and discharging is influence the system thermal behavior and results in capacity loss.

Keywords: Natural gas, Adsorption, Storage, Charging flow rate, Discharging flow rate.

1. INTRODUCTION
Natural gas has been increasingly useful and important as fuel. It was also promisingly used as fuel for vehicle application [1]. Natural gas is more advantageous than other hydrocarbon fuels because offers a greater reduction in carbon monoxide, nitrogen oxides, and non-methane hydrocarbon emissions while having a higher thermal efficiency and practically no particulates compared to gasoline [2]. Natural gas produces a cleaner combustion and a more efficient consumption [3][4]. Natural gas is also an economic fuel for vehicle use. It is cheaper than gasoline and diesel. Currently, natural gas is compressed under high pressure in order be stored in a substantial amount. However, this storage method requires expensive and extensive high-pressure compression facility [5]. For vehicle usage, natural gas is usually stored in a 50 liter cylinder at a very high pressure around 17.2 – 20.7 MPa [2] and is called Compressed Natural Gas (CNG). However, this high-pressure operation, leads to several drawbacks in the storage system such as limited trunk space due to the bulky high-pressure cylinders, complex and expensive fuel supply compressors, and perception of danger associated with the high-pressure systems like cylinder corrosion and possibility of explosive release of compressed gas [6]. These have been the main factor why natural gas has not been used widely for vehicle engine [7].

Storage of natural gas by adsorption could be expected to answer these difficulties of CNG storage. This storage method is called Adsorbed Natural Gas (ANG). In ANG storage, natural gas is adsorbed by a certain high porosity adsorbent material loaded into the storage container. ANG storage operates by enhancing the amount of gas stored when a large portion of gas adsorbs on the adsorbent and markedly improve the storage capacity at lower pressure [8][9]. It takes place at relatively low pressure compare to CNG, which is around 3.5 MPa [10], achievable by single-stage compression and can provide nearly the same capacity of CNG [11]. Compare to CNG storage, the ANG storage stored 67% of the total amount storable with a vessel without adsorbent due to the storage space taken up by adsorbent mass but at 1/6 of its pressure [12]. In other words, although ANG stores less total storable amount of natural gas, but its storage pressure is 83% lower than CNG storage. Figure 1 illustrates the capacity of methane (in g/l) stored in an empty cylinder and in an ANG cylinder with pressurization. Obviously, ANG storage could store more gas than CNG storage at lower pressure.
In this work, the adsorption test is performed on an ANG storage system employing commercial adsorbent to study its storage performance under different gas charging and discharging rate. However, commercial grade methane gas will be used instead of the multi-composition natural gas. The storage capacity of the ANG storage is measured with pressurization from atmospheric pressure to 3.5 MPa and its gas delivery performance by depressurizing to back atmospheric pressure.

2. MATERIALS AND METHODS

2.1 Materials
The materials used in this study are commercial grade palm shell-derived activated carbon adsorbent and commercial grade methane gas with 99.5 % purity. The property of the adsorbent tested and methane used are listed in Table 1 and Table 2.

Table 1 Properties of adsorbent material used in ANG testing

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle Size (MESH)</th>
<th>Micropore Volume (cm$^3$/g)</th>
<th>BET Surface Area (m$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm Shell Activated Carbon (granular)</td>
<td>99</td>
<td>0.214</td>
<td>1012.39</td>
</tr>
</tbody>
</table>

Table 2 Properties of methane used in ANG testing

<table>
<thead>
<tr>
<th>Composition</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH$_4$)</td>
<td>99.5 %</td>
</tr>
<tr>
<td>Oxygen (O$_2$)</td>
<td>100 upm</td>
</tr>
<tr>
<td>Nitrogen (N$_2$)</td>
<td>600 upm</td>
</tr>
<tr>
<td>Hydrogen (H$_2$)</td>
<td>2000 upm</td>
</tr>
<tr>
<td>Non-methane Hydrocarbon (NMHC)</td>
<td>1500 upm</td>
</tr>
</tbody>
</table>
2.2 Adsorption Test Rig
Adsorption test is carried out in a 500-cm$^3$ pressurized gas container made of 316L stainless steel. The ANG cell is attached with a pressure gauge and a temperature probe is installed in the center of the adsorbent-filled cell. It is designed to withstand high pressure and is airtight. Arrangement of the ANG storage adsorption rig is shown schematically in Figure 2. The ANG container is connected to methane supply and controlling section using ¼-inch stainless steel tubing. Valves are installed at the inlet/outlet of the cell to control gas flow in and out of the cell. The measuring unit is consisted of the inlet and outlet gas flow meters, electronic balance and wet test meter.

2.3 Experimental Procedures
The ANG vessel is charged with methane with methane up to 3.5 MPa at varied flow rates. During charging phase, the behavior of temperature and amount of gas uptake measured via the electronic balance is observed. The ANG system is then depressurized right after the charging pressure reached 3.5 MPa to discharge the stored gas. The amount of gas exhausted is measured via wet test meter while temperature change along with pressure drop is closely observed.

![Figure 2 ANG adsorption rig](image)

3. RESULTS AND DISCUSSION
When the vessel is charged with methane, a significant temperature rise occurred as adsorption takes place on the adsorbent substrate. As illustrated in Figure 3, as storage pressure approaching 35 atm (3.5 MPa), gas uptake into the ANG vessel begins to level off while the temperature is recovering gradually after reaching maximum rise because the temperature rise is limited by the duration of charging which permits the heat generated to dissipate before gas uptake finishes at 3.5 MPa. On the other hand, when the ANG storage is discharged upon finishing the filling process, the pressure in the vessel begins to drop and desorption of the stored gas leads to a sharp temperature fall. It was observed that the faster the charging rate, a higher temperature rise takes place while during discharge, the faster the discharging rate, the sharper the pressure and temperature drop. When system reaches depletion pressure which is nearly 0 MPa, a proportion of gas still remains on the adsorbent because of low temperature at this point. The lower the temperature, the more gas left in the vessel. When temperature recovers gradually to ambient condition to achieve thermal equilibrium with surrounding, the residual gas is slowly desorbed over a much longer duration.
The experimental results show that a slower gas charging rate yields a greater amount of gas uptake in the ANG storage. Table 3 shows the storage and delivery capacity obtained at different flow rates. For charging at 1.0 l/min, gas uptake measured is 57.13 g/l which is equivalent to 85.70 l/l compare to 51.18 g/l (76.77 l/l) at 6.0 l/min and 42.76 g/l (64.14 l/l) at 10.0 l/min. Similar results are achieved for the discharge phase. Discharging the gas at 1.0 l/min gives 70.6 l/l of gas volume compare to 68.6 l/l at 6.0 l/min and 63.0 l/l at 10.0 l/min. The amount gas uptake and gas discharged at different flow rates are closely related to storage temperature behavior. This fact is shown in Figure 4. From the figure, a slow charge at 1.0 l/min causes bed temperature to rise 15 °C from room temperature of 28 °C while a typical flow rate of 6.0 l/min yield 38 °C and fast charging at 10.0 l/min yield 47 °C. These extents of heating influence the storage capacity obtained. In a similar way, the extent of cooling during discharge at different flow rates influence gas delivery capacity from the ANG storage. As shown in Figure 5, discharging the stored gas at 1.0 l/min causes temperature to drop 45 °C while discharging at 6.0 l/min yield 69 °C and 10.0 l/min yield 83 °C. Likewise, the extent of temperature drop brings deficiency in delivery capacity. From Table 3, the gas delivery efficiency drops with faster discharging rate. Rate of gas charged and discharged crucially affect the storage temperature behavior, which in turn influence gas storage and delivery capacities.
The condition that greater temperature rise takes place at faster charging rate is due to the exothermic adsorption reaction and to the adsorbent low thermal conductivity that leads to poor heat dissipation, especially for activated carbon adsorbents. Since gas adsorption is inversely proportional with temperature, the temperature rise during charging leads to less gas being adsorbed. Therefore, the faster the charging rate, the higher the temperature rises because greater amount of heat of adsorption is generated per mole of gas charged into the vessel and the lower storage capacity is obtainable. Likewise, faster gas flow rate during discharge leads to lower delivery capacity. When temperature and pressure drop occur during desorption, bearing in mind that lower temperature promotes adsorption, consequently part of the gas molecules tends to remain adsorbed within the adsorbent micropores as the temperature falls. As a result, amount of gas deliverable from the ANG storage decreases and the percentage of this delivery capacity loss get higher when greater temperature drop takes place.

Table 3 ANG storage capacity at 500 psig and delivery performance at depletion under different flow rates

<table>
<thead>
<tr>
<th>Flow rate (l/min)</th>
<th>Storage capacity (l/l)</th>
<th>Delivery capacity (l/l)</th>
<th>Dynamic efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>85.70</td>
<td>70.61</td>
<td>0.81</td>
</tr>
<tr>
<td>6.0</td>
<td>76.77</td>
<td>68.60</td>
<td>0.79</td>
</tr>
<tr>
<td>10.0</td>
<td>64.14</td>
<td>63.00</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Figure 4 Effect of charging rate on gas uptake
4. CONCLUSION
Behavior of the ANG storage pressure and temperature varies with the amount of gas charged into and discharged from the ANG storage. Besides that, the rate of gas charge into and discharge from the ANG storage has an effect on the storage capacity and delivery performance of the adsorbent. Faster charging rate causes higher temperature rise while faster discharging rate causes greater temperature fall which in turn deteriorate both the storage capacity and the delivery efficiency obtained.

5. REFERENCES