Discussion About Carbon-Based Solid-State Hydrogen Storage Materials

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Abstract—Activated carbon, as one type of hydrogen storage material have long been attracted by a measure of researchers. Some of the activated carbon's properties may fall short compared with other materials; their characteristics like high surface area, easy-to-prepare, pretty small diameters, however, keep their status as one of the best choices for hydrogen storage. Carbon nanotube is considered as a promising candidate for solid-state hydrogen storage, and there is quite much research have been conducted to synthesize low-cost carbon nanotube with low absorption temperatures, high gravimetric and volumetric hydrogen storage densities, flexibility, good resistance to oxidation, high hardness, good reversibility and cyclic ability and moderate thermodynamic stability. Carbon fiber has shown its unique advantages among many other solid-state hydrogen storage materials. Carbon fiber might be the best for hydrogen storage since its low gas-solid interaction, tunable texture, surface area, high pore volume and excellent chemical and thermal stability. Additionally, the carbon fiber could also control its pore size for better absorption of a great number of hydrogen molecules. Based on several indexes, this literature introduce above three types of solid-state hydrogen materials, which hopefully are able to be favorable to further researches on relevant fields.

1. Introduction
Hydrogen, which is considered as the cleanest extant energy, has always been thought the most appropriate energy to replace traditional fossil fuels ultimately. However, the core problem grounds how to store hydrogen safely and efficiently. As increasingly more research turns to this field, plenty of novel technologies have been born, including storage in the states of gas, liquid, and solid. Among them, solid-state hydrogen storage has been the most attractive one for scientists all along. And when nanoparticles are also gradually coming into scholars' sights, carbon-based hydrogen storage materials, one type of solid-state hydrogen storage materials, have been a hot topic. This work comprises several solid-state hydrogen storage materials based on carbon. Regarding carbon, several materials have been studied to furthest enhance the storage capacities, and there are three this work will enclose, respectively, activated carbon (AC), carbon nanotube (CNT) and carbon nanofiber (CNF). The content mainly focuses on each...
material's physical and properties, hydrogen storage properties, modification methods, and the characterization methods of these materials and aims to provide valuable resources to relevant experts and scholars to push this field forward.

2. Activated Carbon

2.1 Physical and Chemical Properties
Activated carbon (AC) is becoming increasingly popular in many fields, including industry, medicine, chemistry, environment, fuel storage. So before the discussion about hydrogen storage based on ACs, some properties about AC is worth acknowledging.

Considerable physical properties of AC are simply listed: (i) It has a high surface area: It is estimated that every gram of AC has a surface area of nearly 3,000 m² (32,000 sq ft),[1] which makes it capable of obtaining sufficient activated capacity for varied applications. (ii) It has a high apparent density, which provides a better quality of AC. (iii) AC’s diameter is getting smaller. The specific area of holes simply determines their absorption volume. Generally, the number of micropores (ones with the smallest apertures) occupies the largest proportion, compared with medium and big holes. (iv) Hardness/abrasion number exists to evaluate the AC's resistance of friction. Besides, as a surface-active matter, chemical properties also impact its absorptive properties, which grounds on surface groups' natures and types of forces among such particles.

2.2 Preparation
AC is generally produced by organic feedstocks, including shell, coal, wood, which normally possess a high content of carbon. To accomplish this, there are two methods under consideration: physical activation and chemical activation.

2.2.1 Physical activation
Physical activation, also named gas activation, is a two-stage process that contains carbonization (pyrolysis) and activation.[2] First, the materials were heated up at a temperature of 400-900 °C to burn away water, oil or other volatile components. Then the micropores are exposed, and then the materials were further treated in a thermal environment temperature up to about 1000 °C, also with several oxidizing agents like O₂, water vapor, steam. Therefore, its porous structure will be well developed, and its surface area will be largely improved.[3] Nevertheless, the energy cost during the heating process is considerable. Hence, some innovative activation methods have come out these years, like activation treatment basing on the microwave, plasma, and ultrasound.[4]

2.2.2 Chemical activation
Compared with physical activation, chemical activation is simpler. It has only one step: Mix the materials with agents at a relatively low temperature (about 450-900 °C). Nowadays, frequently applied agents are KOH, ZnCl₂, H₃PO₄, NaOH. This method is increasingly prevalent for the advantages of lower temperatures, larger surface area, better form and properties of final products.[3] And the chemical method is also the main topic of our discussion.

2.2.3 Physical and chemical activation
Now there is also a combination of physical and chemical methods. As a 2019 study showed, these two methods are applied in the whole process flexibly and asynchronously, and the choosing of the method is determined by the material, conditions, or the characters of the experiments. With such a combination, the efficiency will be improved while the cost will also get bigger.[5]
2.3 Hydrogen storage properties

As Hydrogen storage materials, the main aspects of evaluating their properties of H₂ uptake (some studies call it H₂ storage capacity or Cₘ). Following are examples of some recent great-performance AC materials.

2.3.1 Biomass waste to AC

Some researchers use biomass waste as raw materials. In a 2020 study, they collected three types of biomass waste: corn stalk (CC), bagasse (BC) and pine powder (PC), and the activated agents they used are H₃PO₄, ZnCl₂, KOH. Results showed that the most suitable agent is KOH. By applying this, the final product showed the best porous structure and the highest surface area. The pine powder as the feedstock performed the best among all the biomass waste, with the highest H₂ uptake as 2.62 wt% at 1 bar, 77 K.[6]

2.3.2 Tangerine peel to AC

Some researchers also choose tangerine peel (shell) as their feedstock. In 2020, they adopted a cryogenic environment, with ZnCl₂, KOH as the activation agents. Results showed that: Firstly, with a lower temperature (76 K), the capability of hydrogen storage will increase, and under the same condition, ZnCl₂ performed better with a higher H₂ uptake of 1.67 wt% than KOH, at 30 bar, 76 K.[7]

![Diagram](Link to Diagram)

Fig 1. General process of this technology based on the tangerine peel.

2.3.3 Lignin to AC

Lignin is also an appropriate raw material for the preparation of AC. In this 2020 study, researchers study two types of lignin that differ in their contents: One of them is higher in sinapyl (S), and another is higher in guaiacyl (G) (S and G are two types of aromatic monomers). The activation used is the physical method, which is relatively rare nowadays. Results showed activated carbon yielded a surface area of above 1000 m²·g⁻¹, and an H₂ uptake of 1.8 wt%, at 1 bar, 77 K.[8]

2.4 Modification methods

Nowadays, carbon-based hydrogen storage materials are developing faster, while the low storage capacity (0.01-6.7 wt%), high cost, low life-cycle characteristics still limit its large-scale application. Given that some modification methods are required to overcome such obstacles, better promote the application of carbon-based hydrogen storage materials.

2.4.1 Adding acidic groups

A 2019 study introduced a liquid organic hydrogen carriers (LOHC) system based on mixing acid to refine AC's original properties. Two compounds are given: The 2-methylpiperidine system, which finally yields an H₂ uptake of 6.1 wt% in the laboratory. While another is the 2,6-dimethylpiperidine system, with a capacity of 5.5 wt% under the same condition. In the experiments, good stability, fast and reliable H₂ release was demonstrated, while deeper researches are needed to increase the selectivity of the
compounds. All the same, the former still has already surpassed the targets put forward by DOE (5.5 wt%) and EU (5 wt%) for 2020.[9]

2.4.2 Nitridation
A 2017 study put forward a refining method based on nitrogen, specifically by doping N to form microporous activated carbon, hence improved AC’s surface area and the H₂ uptake ability. Compared with previous studies, N-doped activated carbon (NAC) demonstrated the best H₂ uptake property.[10]

Later a 2019 study reported a Pt-N-doped AC with further improved H₂ uptake improved. Meanwhile, they also found that the porous structure mainly dominated the H₂ uptake ability at traditional 77 K temperature, while the Pt content started to proportionally correlate to the H₂ uptake at 298 K.[11]

![Fig. 2. Function of Pt content-H₂ capacity at 298 K and 4 MPa][11]

2.4.3 Nanoparticle technique
Nanoscale material has become an attractive topic in recent years, and more and more scientific research fields are gradually turning to nanoparticles. The same is true for ACs in hydrogen storage. The studied material is named polymer-derived activation carbon (PDAC). The process is shown in Figure 6.

![Fig. 3. A general process of PDAC technology][12]
Having a diameter of only 0.54 nm, PDAC performs superior properties in many aspects. For instance, the H$_2$ uptake capacity is largely improved up to 5.5wt% (as shown in Table 1); In 77 K, ~60 bar, it demonstrates a fully reversible H$_2$ uptake and discharge. And it also shows excellent electrochemical performance. When putting PDAC into an aqueous electrolyte to form a thin electrode, it exhibits a 99% columbic efficiency and a 100% capacitance retention rate after 2,500 charge/discharge circles under a 0.5 mV·s scanning speed, which means with a much smaller diameter, PDAC performed better whether in refining H$_2$ uptake or improving electrochemical energy storage property.[12] And it again shows us the advantages of nanoparticles, and more research is needed to be put on the table about such cutting-edge material.

3. Carbon Nanotube

3.1 Properties

3.1.1 Chemical and physical properties
To construct an efficient, affordable and reliable medium that can store hydrogen reversibly at ambient temperature and pressure for on-board applications has been a current challenge for researchers worldwide. Carbon nanotubes (CNTs) and their composites are considered leading solid-state hydrogen storage materials owing to their unique characteristics. Those characteristics are high surface area, nanoporous structure, tunable properties, low mass density, cage-like structure, chemical stability, dissociation of the hydrogen molecule, and easy synthesis method.

The carbon atom has good bonding properties and can form 3 different hybrid states, including sp, sp$_2$, and sp$_3$. CNTs are composed of carbon-carbon double bonds. Since these covalent bonds are formed by sp$_2$ hybridization, compared with sp$_3$ hybridization, the s orbital component in sp$_2$ hybridization is larger, resulting in high modulus and high strength of CNTs. CNTs are known as the "super-fibers", which have the same hardness comparable to diamond but are more flexible and can be stretched easily, known as. They have extremely high strength and toughness. According to theoretical calculation, the strength of CNTs can achieve 100 times that of steel, while the density is only 1/6 of steel. CNTs are not brittle even though with high toughness and hardness. When enormous external pressure is applied, CNTs will bend, roll and twist, but will probably not break. Once the force is released, it can snap back into place.

CNTs can be divided into two main types: single-walled carbon nanotubes and multi-walled carbon nanotubes. Single-walled carbon nanotubes (SWNTs) Fig 7. (A) Single-walled carbon nanotubes can be considered a perfect monomolecular material formed by rolling a single layer of graphite into a seamless cylindrical tube. Multi-walled carbon nanotubes (MWNTs) Fig.7 (B) can be regarded as composed of multiple SWNTs of different diameters with the same shaft sleeve. Based on the helical direction of the six-sided ring, the SWNTs can be either metallic or semiconducting and can be characterized by the helical vector parameters (n, m) of the CNTs. When n=m, it can be named as armchair carbon nanotube, which is a metallic carbon nanotube. When n=0 or m=0, it is named sawtooth type carbon nanotube. When n, m are unequal integers, they are called helical carbon nanotubes. Serrated and helical carbon nanotubes can be either metallic or semiconductor carbon nanotubes. If n=m= 3k (k is a non-zero integer number), it is a semiconducting carbon nanotube. Otherwise, it is a metallic carbon nanotube.
Fig 4. The intuitive structural formation of (A) SWCNT, (B) MWCNT.

The electrical properties of MWCNs, SWCNs, metallic single-walled carbon nanotubes and metal multi-walled carbon nanotubes are all ballistic conductors, large current by not generating heat, per square centimeter maximum current density can be up to 101 A. CNTs are great heat conduction. The heat transfer coefficient of multi-walled carbon nanotubes is over 3000 W/m*K, which is higher than that of the base plane of natural diamond and graphite atoms. For the base plane of natural diamond and graphite atoms, their thermal conductivity is around 2000 W/m*K. CNTs are good superconducting materials as well. The superconducting temperature of SWNTs is related to their diameter. The smaller the diameter, the higher the superconducting temperature. For example, when the diameter is 1.4 nm, the superconducting temperature is 1.55k, and when the diameter is 0.5 nm, the superconducting temperature is 5k, and as for the diameter is 0.4 nm, the superconducting temperature is 20k.

Due to the small particle size of CNTs, the large specific surface area and strong Van der Waals force between the tubes, entanglement quite often occurs. Generally speaking, the surfactant is added to the solvent to reduce the surface tension of CNTs and change the external states of the system. The dispersion degree of CNTs is directly related to the properties of the materials in the modification result of composites, fabrication of nano-devices and optical applications. Therefore, how to disperse those CNTs and overcome the surface activity of CNTs to prevent agglomeration is difficult in the research field.

According to Zhao et al.’s experimental exploration and data table a[13], analysis can be conducted. From Table 2, an obvious conclusion can be drawn: reasonably changing the distance between inner and outer tube walls can effectively increase multi-walled carbon nanotubes’ physical adsorption hydrogen storage capacity. If the SWCNs as a special case of MWCNs, so for a given diameter of MWCNs (each layer spacing equal), the results revealed that in the table of MWCNs physical adsorption hydrogen storage amount decreases with the increase of the layer number of tubes, that is physical adsorption hydrogen storage amount of MWCNs as SWCNs.
3.1.2 Electrical Properties
As mentioned previously, the structure of a carbon nanotube determines how conductive the nanotube is. When the structure of atoms in a carbon nanotube minimizes the collisions between conduction electrons and atoms, a carbon nanotube is highly conductive. The strong bonds between carbon atoms also allow CNTs to withstand higher electric currents than copper. Electron transport occurs only along the axis of the tube. SWCNs can route electrical signals at speeds up to 10 GHz when used as interconnects on semiconducting devices. Nanotubes also have a constant resistivity.

3.1.3 Thermal Properties
The strength of the atomic bonds in carbon nanotubes allows them to withstand high temperatures. Because of this, carbon nanotubes are very good thermal conductors. Compared to copper wires, commonly used as thermal conductors, carbon nanotubes can transmit over 15 times the amount of watts per meter per Kelvin. The thermal conductivity of carbon nanotubes is dependent on the temperature of the tubes and the outside environment.

3.2 Characterization methods

3.2.1 Infrared spectroscopy, IR
IR is one of the most widely used analysis methods in determining surface functional groups of hydrogen storage materials, especially for functionalized carbon nanotubes. The infrared spectrum is direct evidence of whether the functional group has been grafted to the carbon nanotubes. For instance, Vu et al. synthesized the carboxylic group functionalized carbon nanotube (MWCNT-COOH) by acid treatment. The IR spectrum of the pristine and modified MWCNT shows two extra peaks at 3400-3500 cm⁻¹ and 1000-1200 cm⁻¹, which are assigned to the O-H group and C=O group, indicating the successful grafting of the COOH group on the surface of the carbon nanotube.

3.2.2 Ultraviolet and visible spice-photometry, UV-VIS
It is one of the methods widely used in instrumental analysis. In the process of functionalizing carbon nanotubes, UV-VIS can indicate whether the functionalization is complete due to the characteristic absorption of the conjugated structure of carbon nanotubes. The UV-vis spectra of the original CNTs will show strong Van Hove absorption, while the Van of the modified CNTs Hove absorption band changes smoothly, or even almost no absorption, because the electronic structure of the functionalized carbon nanotubes changes greatly, and some SP hybrid carbon atoms react and change into sp³ hybrid carbon atoms, which can provide evidence for the successful functionalization of the carbon nanotubes.

Table 1. Hydrogen storage capacity of carbon nanotube.[14]

| Kinds of carbon nanotube | The distance between walls/nm | The number density of H₂/nm³ | (H/C) % |
|-------------------------|------------------------------|-----------------------------|--------|
| SWCNT (R=2.03nm)        | 27.93                        | 10.49                       |
| DWCNT (the outer radius R=2.03 nm) | 0.34 | 18.32 | 4.29 |
|                         | 0.61 | 20.67 | 5.17 |
|                         | 0.88 | 21.45 | 5.78 |
| TWCNT (the outer radius R=2.03 nm) | 0.34 | 11.96 | 2.10 |
|                         | 0.61 | 17.59 | 3.61 |
|                         | 0.88 | 21.38 | 5.33 |
3.2.3 Roman spectroscopy
Raman spectroscopy can be used to identify single-walled carbon nanotubes. Due to the unique radial breathing vibration mode of single-walled carbon nanotubes, a characteristic peak will appear in the range of 100-400 cm of Raman spectrum, and the diameter of SWCNs is inversely proportional to the wavenumber of the characteristic peak, Kalbac et al. This characterization method was used to characterize functionalized SWCNs, and it was found that the radial respiration vibration of functionalized SWCNs was greatly reduced. Kalbac also gave the formula to calculate the diameter (D) of carbon nanotubes by RMB peak value (RMB) of 100-400 cm of Raman spectrum: RMB=A/D+B where A=217.8 cm, B= 15.7 cm [18]

3.2.4 X-ray diffraction, XRD
XRD is an analysis based on the internal composition, atomic or molecular structure and morphology of CNTs, which is mainly used to understand material components of the internal structure of atoms or molecules. This characterization method can form information such as the comparison between CNTs and graphite powder diffraction results. Fig.8 shows the angular-dispersive XRD patterns of the SWNT and C60-peapod samples under atmospheric pressure and at room temperature.[19] The SWNT and C60-peapod samples were well crystallized, as illustrated in Fig.8. Since the contribution of the structure factor of C60 chain inside the tube reduces the total structure factor at the peak, which is the 10 position [20], the intensity of the C60-peapod sample is much lower than that of the SWNT sample.

![XRD patterns](image)

Fig 5. Angular-dispersive XRD patterns of pristine (a) SWNT and (b) C60-peapod samples.

3.3 Hydrogen storage property
Heteroatoms modify carbon surface properties, attracting electrons of the neighboring carbon atoms and making them electron deficient. Since hydrogen is likely to be stabilized by transferring an electron to carbon, hydrogen prefers to adsorb on top of the heteroatom-neighboring carbon atoms. Some theoretical calculations showed that nitrogen(N), phosphorus(S), sulfur (S) and boron(B) in CNTs facilitate hydrogen adsorption. Heteroatom doping shows more efficient at near room temperature. However, when the temperature is at 77 K, there is no effect.

Hydrogen storage in a carbon-based material, especially in the CNTs, is intensively studied for applications to the fuel cell, secondary battery, or supercapacitor. There are two kinds of experimental hydrogen storage methods: the high-pressure method 21 and the electrochemical method. Those two methods are more practical for application to the secondary hydrogen battery. It can be easily understood that hydrogen adsorption to the CNTs is a form of ions during the electrochemical process. Although several approaches in experiments, the amount of hydrogen storage capacity is not achieved in useful
level yet. A difficulty caused by the absence of a theoretical model in an atomic scale for hydrogen adsorption and storage mechanism.

DF calculations can be used to identify several hydrogen adsorption geometries. And the C-H bonds changed the electronic properties of metallic CNT to semiconductors. This suggests that the electrochemical hydrogen storage process requires additional or doping conductive materials to the nanotube electrode.

3.4 Modification means
Nanocrystalline metals, metal oxides, or hydrides can be doped/embedded into the original carbon nanotubes by in-situ reduction, wet impregnation, high-energy ball milling and sputtering. As mentioned above, characterization techniques for primary and composite materials can be used to study morphology, thermal, qualitative, quantitative, and elemental analysis. Volumetric and gravimetric methods usually measure the hydrogen absorption capacity of nanocomposites. The hydrogen storage performance of the composite was exponentially improved compared to the original carbon nanotubes, thanks to the hydrogen spillover mechanism from activation, acidification, purification, ball milling and physical adsorption of metal catalysts onto the carbon nanotubes. Carbon nanotubes and composites have a single effect on hydrogen pressure. Compared with the original carbon nanotubes, the composite material has a higher hydrogen absorption rate and remarkably cyclic stability in the continuous adsorption cycle.

Hydrogen plasma etching of CNTs was done in a microwave plasma generator, as shown in Fig. 4. Microwave plasma etching and Pd decoration methods were employed for the modification of CNTs. HRTEM observation and Raman spectroscopy showed that the defects of the nanotube wall increased after etching. These defects provide more hydrogen channels in the middle layer and hollow interior of the nanotubes. At the same time, hydrogen absorption test results show that the hydrogen storage performance of carbon nanotubes is better than the original sample to some extent under the environmental pressure of 10.728 MPa. In addition, the hydrogen storage capacity of palladium-modified carbon nanotubes is 4.5 %, which is about three times higher than that of unmodified carbon nanotubes (about 1.5 %).

Fig 6. Microwave plasma generator: (1) micro-wave source, (2) closed-loop control, (3) three-bolt adjustor, (4) coupling antenna, (5) plasma ball, (6) resonant cavity and (7) inlet of inert gas.

4. Carbon Fiber

4.1 Physical and Chemical Properties
Since energy security has been threatened as less and less fossil fuel resources have been used up, scientists have turned to find new types of energy. Hydrogen came out to be the attractive one as it can almost replace fossil fuels and could produce no harmful byproducts. Thus the task has turned to be
finding the most appropriate hydrogen storage materials. After comparing liquefaction, high-pressure compression, solid-state materials and porous materials, scientists find porous materials to have benefits, including fast reaction kinetics, high absorption capacity and a higher level of safety. By comparing different types of porous materials, carbon-based porous materials might be the most appropriate, like carbon fibers. In detail, carbon fiber might be the best one since its low gas-solid interaction, tunable texture, surface area, high pore volume and excellent chemical and thermal stability. Additionally, the carbon fiber could also control its pore size for better absorption of a great number of hydrogen molecules.

4.2 The hydrogen storage capacity of PCF APCF and Pd deposited APCF

Researchers have made a comparison of porous carbon fiber (PCF), activated porous carbon fiber (APCF), and Pd deposited activated carbon fiber (Pd-APCF) based on their surface area microporosity and hydrogen storage capacity. The comparisons are based on the samples under the condition of 77K and 10MPa, in Table 1 and Figure 1c. It shows clearly an increase in the capacity when it is below 500 kPa, while it becomes saturated at 2 MPa. In Figure 1c, the CF, ACF, PCF_H 0.3 and APCF_0.3 with the different surface areas have different hydrogen storage capacities of 0.07, 1.35, 2.87, and 5.14 wt%, at 77K and 10MPa, respectively. That leads to the result that the hydrogen storage capacity might be proportional to the BET surface area. Moreover, the result is also strongly supported by Chahine's rule that it could absorb $2.00 \times 10^3$ wt% hydrogen gas per unit specific surface area of the examined carbon materials.

Moreover, scientists have also particularly found that APCF_H 0.3 shows the best hydrogen storage capacity despite Pd-deposited materials. Respectively, the greatly improved hydrogen storage capacity could come from microporosity that might play a key role in hydrogen storage. The reason for the phenomenon was predicted to be that micropores with a great quantity of hydrogen storage lie in APCF_H 0.3 compared with others. And as tested, the micropore in PCF_H 0.3 is narrower with an average width of 1.05 nm in APCF_H 0.3. Thus, the reason might be clear that the improvement of APCF_H 0.3 is due to the contribution of the narrower micropore, which is about only 0.8-1.2 nm.

From the above observations, it could be found that the largest micropore volume of APCF_H 0.3 greatly enhances the hydrogen storage capacity (Table 3). Therefore, a rough conclusion can be made that both the micropore size, especially in the case of a 1-nm pore width, and the micropore volume, might play an important role that increases the hydrogen storage capacity, respectively. Also, to further improve the hydrogen capacity, Pd nanoparticles were electrode-posed onto the APCF_H 0.3. As Pd nanoparticles have been deposited on APCF_H 0.3, the declines have varied significantly, including that the BET surface area falls to 2611 m²·g⁻¹, the percentage of micropore volume in total pore volume falls by 4.1 %. The total pore volume falls to 1.42 cm³·g⁻¹. Additionally, the number of pores is also decreased slightly, which would constitute effective hydrogen storage (0.8 - 1.2 nm). It is also observed that with the increase of the concentration of PdCl₂, the surface area, the fraction of micropores and the pore volume also decreased slightly. Such a result might show that the Pd nanoparticles might cover the pore of APCF_H 0.3. Through the examination, the Pd nanoparticles do aggregate on the surface of the APCF_H 0.3 and also cover most of the fibers' pore to be the concentration when the PdCl₂ solution did increase.

Table 2. Surface area, microporosity, and hydrogen storage capacity of samples at 77 K and 10 MPa in comparison with reported literature.[21]

| Samples    | $S_{BET}$ (m²·g⁻¹) | $V_p$ (cm³·g⁻¹) | $V_{micro}$ (cm³·g⁻¹) | $W_{average}$ (nm) | H₂ Uptake (wt%) |
|------------|---------------------|-----------------|------------------------|-------------------|-----------------|
| CF         | 11                  | 0.06            | 0.01 (16.7)            | 1.81              | 0.07            |
| ACF        | 316                 | 0.21            | 0.12 (57.1)            | 1.13              | 1.35            |
| PCF_H 0.3  | 889                 | 0.47            | 0.34 (72.3)            | 1.12              | 2.87            |
Fig 7. Hydrogen uptakes of CF, ACF, PCF_H 0.3, APCF_H 0.3, and Pd 0.5/APCF_H 0.3 (PdCl₂ solution concentration: 0.5 mM).[21]

To sum up, these results might indicate a competitive relationship between the physisorption by alkali activation and chemisorption by the spillover effect [22-24]. Thus, for the application of metal-deposited carbon fiber in hydrogen storage, the effect of metal nanoparticles on micropore volume and pore size of the metal deposited-carbon fiber would have to be considered together with a spillover effect [25, 26].

5. Conclusion

AC, CNTs and CNFs are three types of solid-state hydrogen storage methods with favorable hydrogen-generated properties, high hydrogen storage capacities, and good kinetic property for hydrogen storage. Although the problems can be improved by surface modification and catalyst addition, further research is still needed. There is no doubt that no perfect choice of hydrogen storage materials to meet the target set can be found, but still, a better choice can be conducted. This article contains various types of AC, CNTs and CNFs, while more information about them are still unknown. More researches need to be done regarding the environmental and health impacts of producing large quantities of them. AC, CNT and CNF will play a significant role in a wide range of commercial applications. Not only will they help create some cutting-edge tech gadgets, but they may also help solve the world's energy problems. It is believed that this article will purvey a valuable reference for all scientists and scholars involved in solid-state hydrogen storage materials research.
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