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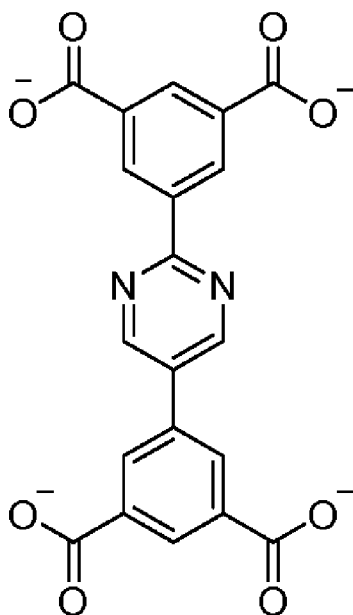
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(54) Title: A POROUS METAL-ORGANIC FRAMEWORK WITH PYRIMIDINE GROUPS

(57) Abstract: Disclosed herein are metal-organic frameworks (MOF) and uses thereof, including those comprising a repeat unit of the formula $[Cu_2L(H_2O)_2] \cdot 5DMF \cdot 3H_2O$, wherein L is a ligand of the formula: These are useful for many applications, including in the purification of hydrogen gas from production byproducts CH_4 and CO_2 , sensing, heterogeneous catalysis, drug delivery, lithium sulfide battery, membrane and analytical devices.

DESCRIPTION

A POROUS METAL-ORGANIC FRAMEWORK WITH PYRIMIDINE GROUPS

5

BACKGROUND OF THE INVENTION

The application claims priority to U. S. Provisional Patent Application No. 61/968,849 filed March 21, 2014, which is incorporated herein by reference in its entirety.

I. Field of the Invention

10 The present disclosure relates generally to the fields of chemistry and materials science. More particularly, it concerns metal-organic frameworks, compositions thereof and methods use thereof, including for separating gas molecules, sensing, heterogeneous catalysis, drug delivery, lithium sulfide battery, membrane and analytical devices.

II. Description of Related Art

15 Microporous metal-organic frameworks (MOFs) have emerged as a new type of porous materials for gas storage, separation, sensing and heterogeneous catalysis. The tunable pores and the immobilized functional sites within such microporous MOFs have enabled them to direct specific recognition of certain molecules based upon size and functionality.

Control of pore sizes and pore surfaces within porous materials is useful for their ability
20 to selective recognize and thus separation of small molecules, and the pores within such porous MOFs can be systematically modified simply by the change the secondary building blocks (SBUs), changing the organic bridging linkers, or the control of the framework interpenetration (Deng *et al.*, 2010; Chen *et al.*, 2010; Ma *et al.*, 2010; Horike *et al.*, 2009). To tune the micropores to induce their size specific encapsulation of small gas molecules, various series of
25 microporous metal-organic framework materials have emerged as promising microporous media for the recognition and separation of small gas molecules (Kitaura *et al.*, 2004; Chen *et al.*, 2004; Cho *et al.*, 2006; Liu *et al.*, 2010; Murray *et al.*, 2010; Ma *et al.*, 2009; McKinlay *et al.*, 2008; Dubbeldam *et al.*, 2008; Chen *et al.*, 2006; Finsy *et al.*, 2008; Bae *et al.*, 2010; Zhang *et al.*, 2008; Dybtsev *et al.*, 2004; Li *et al.*, 2009; Vaidhyanathan *et al.*, 2006; Nuzhdin *et al.*, 2007;
30 Dybtsev *et al.*, 2006; Chen *et al.*, 2008).

The discovery of new energy resources, particularly natural gas in the form of shale gas in the United States, is facilitating the implementation of natural gas as a viable alternative

energy source. The United States has the commercialization capability to produce large-scale shale gas at a cheaper cost than other countries, which makes natural gas appealing as a new fuel (Armor, 2013). In order to accelerate such a fuel switching from coal/petroleum to natural gas, suitable materials for natural gas storage and transportation need to be developed. While
5 Compressed Natural Gas (CNG), stored as supercritical fluid at room temperature and 200-300 bar in steel cylinder, might be still suitable for large vehicles such as trucks, Adsorbed Natural Gas (ANG) is better suited for daily use cars for both the cost and safety reasons.

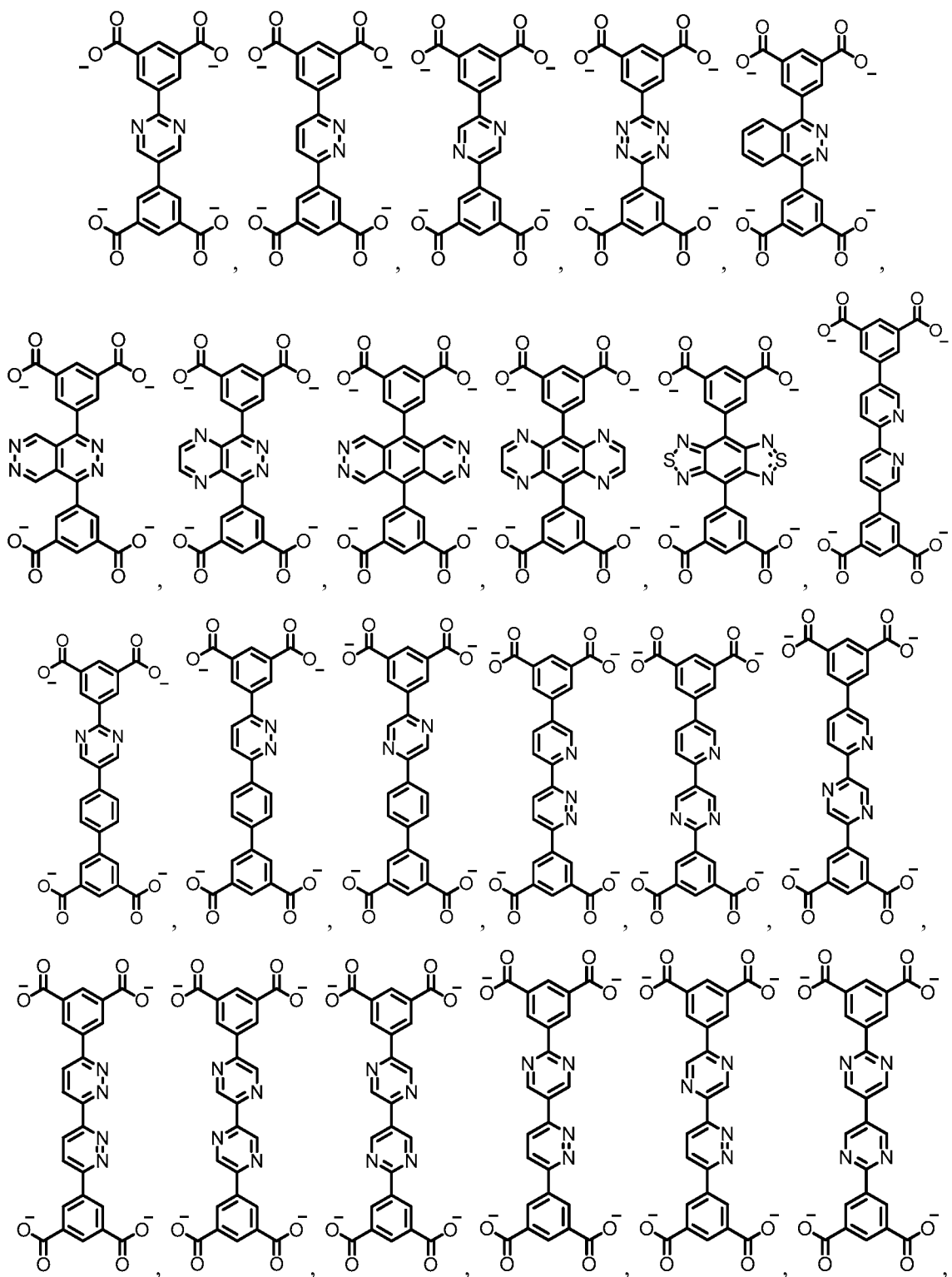
Among the diverse porous adsorbents for methane storage (methane is the main component in natural gas), porous metal-organic frameworks (MOFs) are promising for such a
10 purpose because of their high porosities, tunable pores and easily immobilized functional sites to optimize their storage capacities (O’Keeffe *et al.*, 2012; Horike *et al.*, 2009; Férey and Serre, 2009; Zhang *et al.*, 2012; Yan *et al.*, 2013; Wang *et al.*, 2013; Sumida *et al.*, 2012; Getman *et al.*, 2012; Wu *et al.*, 2012; Wilmer *et al.*, 2013; Wu *et al.*, 2009; Park and Suh, 2013 and Jiang and Xu, 2011). BASF has commercialized some prototypic MOFs as well as demonstrated
15 model vehicles fueled with natural gas by making use of BASF MOF materials (BASF MOF Materials for Energy Storage). In order to fully implement natural gas fuel systems for vehicles, target adsorbents with high methane storage capacities need to be developed. The Advanced Research Projects Agency–Energy (ARPA-E) of the U.S. Department of Energy (DOE) developed methane storage targets to guide the research on adsorbent based methane storage
20 with the goal of a volumetric storage capacity of $350 \text{ cm}^3 \text{ (STP) cm}^{-3}$ for the adsorbent material at room temperature (DOE MOVE Guidelines). Without the consideration of packing loss, according to the guidelines, the volumetric storage capacity needs to be higher than $263 \text{ cm}^3 \text{ (STP) cm}^{-3}$, equivalent to that of CNG at 250 bar and 298 K. Furthermore, the DOE set a target of the gravimetric energy density of $0.5 \text{ g(CH}_4\text{) g}^{-1}\text{(adsorbent)}$ for new adsorbent based methane
25 storage materials.

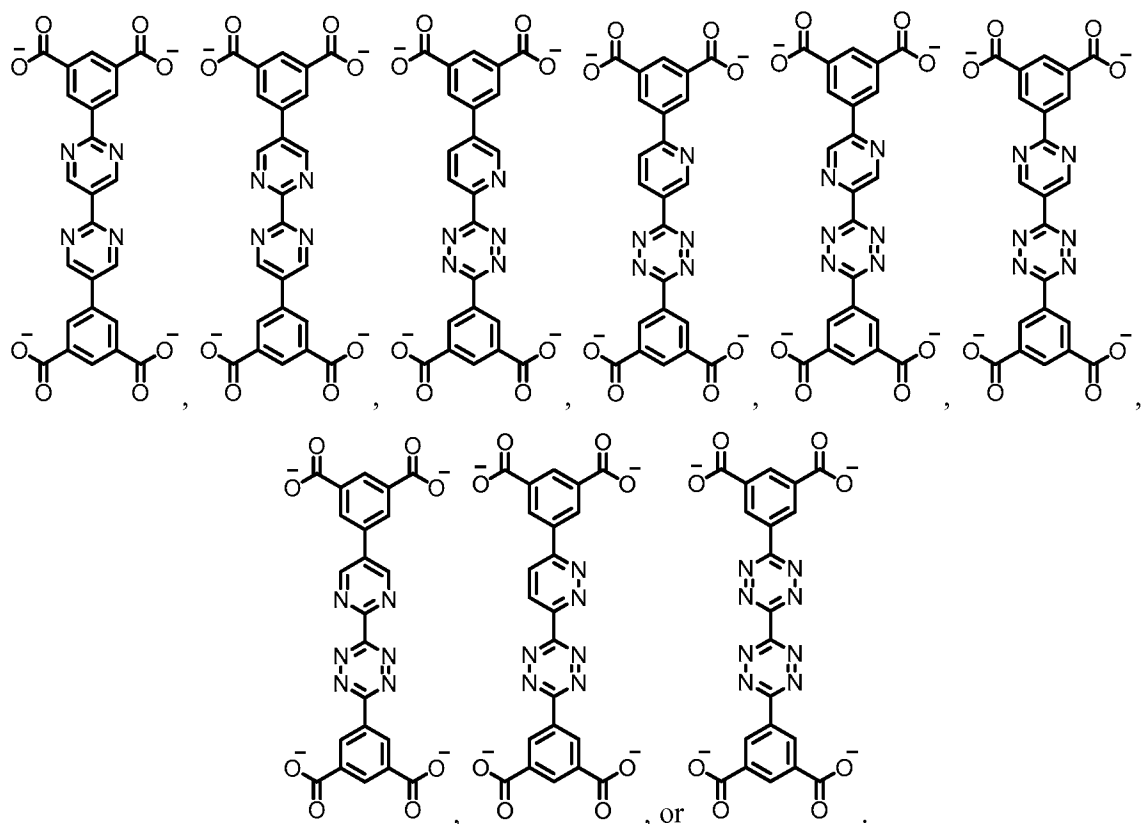
Although the potential of MOF materials for methane storage has been conceptually established, reaching the DOE targets in practice has been challenging. Since the discovery of the first MOFs for methane storage, (Kondo *et al.*, 1997 and Eddaoudi *et al.*, 2002) significant progress has been made to improve the methane storage capacities of MOF materials over the
30 past decade; however, their storage capacities are still far away from the DOE target (He *et al.*, 2012 and Makal *et al.*, 2012). Recently, three independent groups realized a unique MOF, HKUST-1 (Chui *et al.*, 1999), for high methane storage with volumetric storage capacity of $259\text{--}267 \text{ cm}^3 \text{ (STP) cm}^{-3}$ at 65 bar and room temperature (Peng *et al.*, 2013 and Mason *et al.*, 2014). This was the first MOF material whose volumetric methane storage capacity to reach the DOE
35 target if packing loss is not considered.

The saturated gravimetric methane storage capacities of MOF materials are basically determined by their porosities (pore volumes and/or BET surface areas) (Peng *et al.*, 2013; He *et al.*, 2013; Kong *et al.*, 2013 and Feldblyum *et al.*, 2013). In order to optimize volumetric methane storage capacities, MOFs balance porosities and framework densities with a high
5 densities of functional sites/groups and pore cages for the recognition of methane molecules (He *et al.*, 2013; Gedrich *et al.*, 2010; Ma *et al.*, 2008 and Guo *et al.*, 2011). The MOF-505 series of MOFs of NbO type structures meet these criteria and are of interest (Chen *et al.*, 2005 and Lin *et al.*, 2006).

SUMMARY OF THE INVENTION

In some aspects, the invention provides a metal-organic framework (MOF) comprising a repeat unit of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$ (**UTSA-76**), wherein L is a ligand of the formula or a protonated, unprotonated, partially protonated, or partially unprotonated form thereof:





In some embodiments, the metal organic framework is activated for sorption of gas molecules. In some embodiments, the MOF further comprises one or more than one type of guest molecule. In some embodiments, the guest molecule is a solvent molecule. In some
 5 embodiments, the solvent molecule is water. In other embodiments, the solvent molecule is *N,N'*-dimethylformamide.

In some embodiments, the MOF further comprises about between one and eight *N,N'*-dimethylformamide and between one and eight water molecules per repeat unit. In other
 10 embodiments, the MOF is further comprised of about five *N,N'*-dimethylformamide and three water molecules per repeat unit. In some cases, the solvent molecules occupy the pores of the MOF. In some embodiments, the MOF has the formula: $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$.

In some embodiments, one type of guest molecule is a gas molecule. In some cases, the gas molecule is H_2 , CO_2 , or CH_4 . In some embodiments, the gas molecule is CO_2 . In some
 15 embodiments, the gas molecule is CH_4 . In other embodiments, the gas molecule is H_2 . In other cases, the gas molecule is CO_2 and CH_4 .

In some instances, MOF is substantially free of solvent molecules.

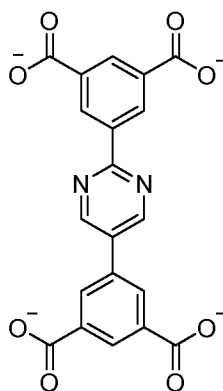
In some cases, the MOF has a weight percentage at least 90% attributable to repeat units of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$. In other cases, the MOF has a weight percentage at
 20 least 95% attributable to repeat units of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$. In some cases, the MOF has a weight percentage at least 99% attributable to repeat units of the formula

$[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$. In other instances, the metal-organic framework has been adhered to a fixed surface.

In some embodiments, the repeat unit of the MOF is a ligand of the formula listed in **Additional Ligands**.

5 In another aspect, the invention provides methods of separating two or more compounds using an MOF comprising:

- (a) obtaining a metal-organic framework (MOF) comprising a repeat unit of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$, wherein L is a ligand of formula:



10 (b) combining the MOF with a mixture comprising a first compound and a second compound; and

- (c) separating the first compound from the second compound.

In some embodiments, the MOF is activated for sorption of gas molecules. In some embodiments, the separation is based on their differential sorption rate within the MOF.

15 In some embodiments, the first compound is a gas molecule. In some embodiments, the first compound is H_2 . In some embodiments, the second compound is a gas molecule. In some embodiments, the second compound is CH_4 or CO_2 . In some embodiments, the second compound is CH_4 . In other embodiments, the second compound is CO_2 . In some embodiments, the mixture further comprises a third compound. In some embodiments, the third compound is
20 CH_4 . In other embodiments, the third compound is CO_2 . In some embodiments, the mixture comprises H_2 and CH_4 . In other embodiments, the mixture comprises H_2 and CO_2 . In other embodiments, the mixture comprises H_2 , CH_4 , and CO_2 .

In some embodiments, the separation is carried out at a pressure from about 10 kPa to about 50 mPa. In some cases, the separation is carried out at a pressure from about 2 mPa to
25 about 20 mPa. In some embodiments, the separation is carried out at a pressure from about 4 mPa to about 15 mPa

In some embodiments, the MOF is adhered to a fixed bed surface. In some embodiments, the MOF is packed in an absorber. In some embodiments, the absorption is carried out at a temperature from about -50°C to about 50°C .

In other aspect, the invention provides methods of using the MOFs provided herein for sensing, heterogeneous catalysis, drug delivery, and as a component of, for example, a lithium sulfide battery, a membrane, and/or an analytical device.

Other objects, features and advantages of the present disclosure will become apparent from the following detailed description. It should be understood, however, that the detailed description and the specific examples, while indicating specific embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings form part of the present specification and are included to further demonstrate certain aspects of the present disclosure. The invention may be better understood by reference to one of these drawings in combination with the detailed description of specific embodiments presented herein.

FIG. 1 shows PXRD patterns of as-synthesized UTSA-76 (middle) and activated UTSA-76a (top) along with the simulated XRD pattern from the single-crystal X-ray structure (bottom).

FIG. 2 shows TGA curves of as-synthesized UTSA-76.

FIG. 3 shows nitrogen isotherm at 77 K with consistency and BET plots for the activated UTSA-76a sample.

FIG. 4 shows the total volumetric high-pressure methane sorption isotherms of UTSA-76 at different temperatures. Filled and open symbols represent adsorption and desorption data, respectively.

FIG. 5 shows a comparison of the total methane uptake at different temperature of UTSA-76a and NOTT-101a.

FIG. 6 shows the comparison of the total volumetric (top) and gravimetric (bottom) methane uptake at 298 K of UTSA-76a and NOTT-101a.

FIG. 7 shows the schematic of the determination of deliverable amount of UTSA-76, defined as the difference in uptake between 65 bar and 5 bar.

FIG. 8 shows experimental (circles), Le Bail fitted (line), and difference (line below observed and calculated patterns) PXRD profile for activated UTSA-76 at 298 K (Cu Ka radiation). Vertical bars indicate the calculated positions of Bragg peaks. Refined lattice parameters: $a=18.574(2)$ Å and $c=38.022(8)$ Å. $R_p=0.071$, $R_{wp}=0.090$. Corresponding crystal density: 0.699 g/cc.

FIG. 9 shows experimental (circles), Le Bail fitted (line), and difference (line below observed and calculated patterns) PXRD profile for activated NOTT-101 at 298 K (Cu Ka radiation). Vertical bars indicate the calculated positions of Bragg peaks. Refined lattice parameters: $a=18.578(2)$ Å and $c=38.469(8)$ Å. $R_p=0.071$, $R_{wp}=0.090$. Corresponding crystal density: 0.688 g/cc.

FIG. 10 shows pore size distributions (PSDs) of UTSA-76a and NOTT-101a. PSDs were calculated using the method of Gubbins et al (Spek, 1999). The van der Waals diameters of the framework atoms were adopted from the Cambridge Crystallographic Centre.

FIG. 11 shows the variation of the total energy as the central rings of the UTSA-76 and NOTT-101 linker are rotated around the linker backbone, derived from DFT calculations. The rotational barrier for UTSA-76 is particularly small, less than half of that for NOTT-101

FIG. 12 shows on the top: A comparison of the normalized elastic neutron scattering intensity vs. temperature for UTSA-76a and NOTT-101a and on the bottom: Temperature-dependent atomic mean-square-displacements, derived from data in the top panel.

FIG. 13 shows the comparison of Q_{st} for CH_4 adsorption for UTSA-76 and NOTT-101.

FIG. 14 shows the derivation of Q_{st} for CH_4 adsorption for UTSA-76a. The gray line in the Q_{st} plot is obtained from virial fitting of the absolute adsorption isotherm data. The fit and the virial coefficients are also shown. The black line in the Q_{st} plot is obtained from the raw isotherm data using cubic spline method without any fitting.

FIG. 15 shows the derivation of Q_{st} for CH_4 adsorption for NOTT-101a. The gray line in the Q_{st} plot is obtained from virial fitting of the absolute adsorption isotherm data. The fit and the virial coefficients are also shown. The black line in the Q_{st} plot is obtained from the raw isotherm data using cubic spline method without any fitting.

FIG. 16 shows excess volumetric high-pressure methane sorption isotherms of UTSA-76 at different temperatures. Filled and open symbols represent adsorption and desorption data, respectively.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

I. Definitions

“Metal-organic frameworks” (MOFs) are framework materials, typically three-dimensional, self-assembled by the coordination of metal ions with organic linkers exhibiting porosity, typically established by gas adsorption. The MOFs discussed and disclosed herein are at times simply identified by their repeat unit as defined below without brackets or the subscript n. A mixed-metal-organic frameworks (M'MOF) is a subset of MOFs having two or more types of metal ions.

A “repeat unit” is the simplest structural entity of certain materials, for example, frameworks and/or polymers, whether organic, inorganic or metal-organic. In the case of a polymer chain, repeat units are linked together successively along the chain, like the beads of a necklace. For example, in polyethylene, $[-CH_2CH_2-]_n$, the repeat unit is $-CH_2CH_2-$. The subscript “n” denotes the degree of polymerisation, that is, the number of repeat units linked together. When the value for “n” is left undefined, it simply designates repetition of the formula within the brackets as well as the polymeric and/or framework nature of the material. The concept of a repeat unit applies equally to where the connectivity between the repeat units extends into three dimensions, such as in metal organic frameworks, cross-linked polymers, thermosetting polymers, etc. Note that for MOFs the repeat unit may also be shown without the subscript n.

“Pores” or “micropores” in the context of metal-organic frameworks are defined as open space within the MOFs; pores become available, when the MOF is activated for the storage of gas molecules. Activation can be achieved by heating, *e.g.*, to remove solvent molecules.

“Multimodal size distribution” is defined as pore size distribution in three dimensions.

“Multidentate organic linker” is defined as ligand having several binding sites for the coordination to one or more metal ions.

In addition, atoms making up the compounds of the present invention are intended to include all isotopic forms of such atoms. Isotopes, as used herein, include those atoms having the same atomic number but different mass numbers. By way of general example and without limitation, isotopes of hydrogen include tritium and deuterium, and isotopes of carbon include ^{13}C and ^{14}C . Similarly, it is contemplated that one or more carbon atom(s) of a compound of the present invention may be replaced by a silicon atom(s). Furthermore, it is contemplated that one or more oxygen atom(s) of a compound of the present invention may be replaced by a sulfur or selenium atom(s).

Any undefined valency on a carbon atom of a structure shown in this application implicitly represents a hydrogen atom bonded to the atom.

The use of the word “a” or “an,” when used in conjunction with the term “comprising” in the claims and/or the specification may mean “one,” but it is also consistent with the meaning of
5 “one or more,” “at least one,” and “one or more than one.”

Throughout this application, the term “about” is used to indicate that a value includes the inherent variation of error for the device, the method being employed to determine the value, or the variation that exists among the study subjects.

The terms “comprise,” “have” and “include” are open-ended linking verbs. Any forms
10 or tenses of one or more of these verbs, such as “comprises,” “comprising,” “has,” “having,” “includes” and “including,” are also open-ended. For example, any method that “comprises,” “has” or “includes” one or more steps is not limited to possessing only those one or more steps and also covers other unlisted steps.

The term “effective,” as that term is used in the specification and/or claims, means
15 adequate to accomplish a desired, expected, or intended result.

The term “hydrate” when used as a modifier to a compound means that the compound has less than one (*e.g.*, hemihydrate), one (*e.g.*, monohydrate), or more than one (*e.g.*, dihydrate) water molecules associated with each compound molecule, such as in solid forms of the compound.

20 The term “saturated” when referring to an atom means that the atom is connected to other atoms only by means of single bonds.

The above definitions supersede any conflicting definition in any of the reference that is incorporated herein by reference. The fact that certain terms are defined, however, should not be considered as indicative that any term that is undefined is indefinite. Rather, all terms used are
25 believed to describe the invention in terms such that one of ordinary skill can appreciate the scope and practice the present invention.

Example 1: Methods and Materials

1. General Procedures and Materials.

All reagents and solvents were commercially available and used without further purification.
30 Dimethyl 5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl) isophthalate was prepared according to the literature procedure (Chen *et al.*, 2010). ¹H NMR spectra were recorded on a Varian Mercury 500 MHz spectrometer using tetramethylsilane (TMS) as internal standards. The coupling constants reported in Hertz. FTIR spectra were performed on a Bruker Vector 22 spectrometer at room temperature. The elemental analyses were performed with Perkin–Elmer

240 CHN analyzers from Galbraith Laboratories, Knoxville. Thermogravimetric analyses (TGA) were carried out using a Shimadzu TGA-50 analyzer under a nitrogen atmosphere with a heating rate of 5 °C min⁻¹. Powder X-ray diffraction (PXRD) patterns were measured by a Rigaku Ultima IV diffractometer operated at 40 kV and 44 mA with a scan rate of 1.0 deg min⁻¹. The
5 neutron scattering experiment was performed on the High Flux Backscattering Spectrometer at the NIST Center for Neutron Research, which has an incident neutron wavelength of 6.27 Å (2.08 meV) and a resolution of 0.8 meV eV full width at half maximum (FWHM) (Meyer *et al.*, 2003). Elastic neutron scattering intensities were scanned in the T range of 10 K – 320 K, with a ramping rate of 1 K/min.

10 2. Gas sorption Measurements.

A Micromeritics ASAP 2020 surface area analyzer was used to measure gas adsorption isotherms. To remove all the guest solvents in the framework, the fresh sample of UTSA-76 was guest-exchanged with dry acetone at least 10 times, filtered and degassed at room temperature (296 K) for one day, and then at 373 K for another 20 hours until the outgas rate was 5 μmHg
15 min⁻¹ prior to measurements. The activated sample of UTSA-76a was maintained at 77 K with liquid nitrogen. High-pressure CH₄ sorption isotherms were measured using a Sieverts-type apparatus. A detailed description of the experimental setup, calibration, and the isotherm can be found in a previous publication (Meyer *et al.*, 2003).

3. Single-crystal X-ray crystallography.

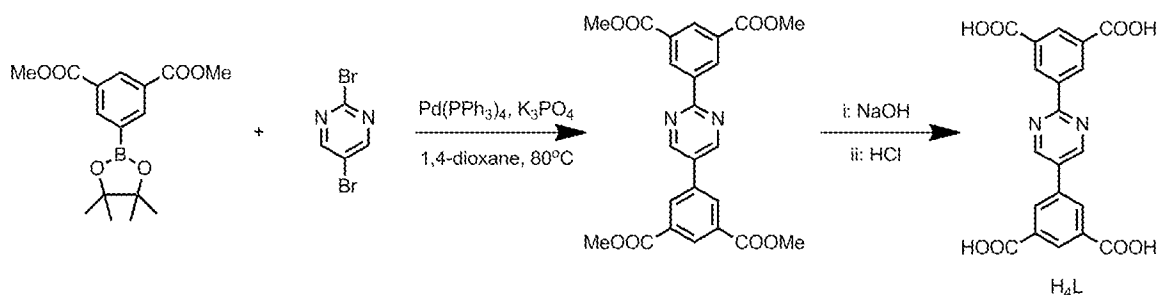
The crystal data were collected on an Agilent Supernova CCD diffractometer equipped with a graphite-monochromatic enhanced Cu Kα radiation ($\lambda = 1.54184$ Å) at 100 K. The datasets were corrected by empirical absorption correction using spherical harmonics, implemented in the SCALE3 ABSPACK scaling algorithm. The structure was solved by direct methods and refined by full matrix least-squares methods with the SHELX-97 program package (Zhou *et al.*, 2007).
25 The central pyrimidine ring of organic ligand is disordered, which was refined as disordered model with occupancies of 0.25 for C7, 0.25 for N1, 0.25 for C7', and 0.25 for N1'. The solvent molecules in the compound are highly disordered. The SQUEEZE subroutine of the PLATON software suit was used to remove the scattering from the highly disordered guest molecules (Sheldrick, 1997). The resulting new files were used to further refine the structures. The H
30 atoms on C atoms were generated geometrically.

Example 2: Synthetic Methods

Disclosed herein are the synthesis, structures, and sorption studies of one new MOFs, [Cu₂L(H₂O)₂]·5DMF·3H₂O (UTSA-76). The organic linker H₄L was readily synthesized by Suzuki cross-coupling reaction of 2,5-dibromopyrimidine and 5-(4,4,5,5-tetramethyl-1,3,2-

dioxaborolan-2-yl) isophthalate followed by hydrolysis and acidification in good yield. UTSA-76 was synthesized by a solvothermal reaction of H₄L and Cu(NO₃)₂·2.5H₂O in DMF/H₂O/MeCN mixture solvents with the addition of a small amount of hydrochloric acid at 80 °C for 1 days to afford blue block crystals. The formula was determined as [Cu₂L(H₂O)₂]·5DMF·3H₂O by single-crystal X-ray diffraction analysis, thermogravimetric analysis (TGA, **FIG. 1**) and the elemental analysis. The phase purity of the bulk material was confirmed by powder X-ray diffraction (PXRD, **FIG. 2**).

Scheme 2. Synthetic routes to the organic linker H₄L.



Tetramethyl 5, 5'-(pyrimidine-2, 5-diyl)diisophthalate. 2, 5-Dibromopyrimidine (1.18 g, 5 mmol), 5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl) isophthalate (3.52 g, 11 mmol), K₃PO₄ (2.55 g, 12 mmol) and tetrakis(triphenylphosphine) palladium(0) (0.3 g, 0.26 mmol) were dissolved in dry 1,4-dioxane (80 mL) under N₂ atmosphere. The mixture was stirred at 80 °C for two days. After that, the precipitate was collected by filtration, washed with 1,4-dioxane for several times, and then recrystallized in toluene to obtain the pure product. Yield: 56% (1.3 g). ¹H NMR (500 MHz, CDCl₃, ppm): δ 9.38 (s, 2H), 9.15 (s, 2H), 8.86 (s, 1H), 8.80 (s, 1H), 8.53 (s, 2H), 4.03 (s, 12H).

5, 5'-(pyrimidine-2, 5-diyl)diisophthalic acid (H₄L). Tetramethyl 5,5'-(pyrimidine-2,5-diyl)diisophthalate (1.3 g, 2.8 mmol) was suspended in 50 mL THF, and then a 2M KOH aqueous solution (75 mL) was added. The mixture was stirred under reflux overnight until it became clear. After that THF was removed under reduced pressure and dilute HCl was then added to the remaining aqueous solution to acidify pH = 2. The precipitate was collected by filtration, washed with water for several times, and dried to afford white powder. Yield: 1.08 g (95%). ¹H NMR (500 MHz, DMSO-*d*₆, ppm): δ = 13.11 (s, 4H), 9.31 (s, 2H), 9.13 (s, 2H), 8.54 (s, 1H), 8.50 (s, 2H), 8.50 (s, 1H). ¹³C NMR (DMSO-*d*₆, ppm): δ = 166.69, 166.65, 161.42, 156.24, 137.96, 135.20, 132.79, 132.57, 132.36, 131.95, 130.80, 130.45.

Synthesis of UTSA-76. A mixture of the organic linker H₄L (15.0 mg, 0.037 mmol) and Cu(NO₃)₂·2.5H₂O (30.0 mg, 0.129 mmol) was dissolved into a 8 mL mixed solvent (DMF/MeCN/H₂O, 6/1/1, v/v) in a screw-capped vial (20 mL). 50 μL of 37% HCl were added. The vial was capped and heated in an oven at 80 °C for 24 h. Blue block crystals were obtained

by filtration and washed with DMF several times to afford UTSA-76 in 65% yield. UTSA-76 has a formula of $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$, which was obtained based on the basis of single-crystal X-ray structure determination, elemental analysis and TGA. Anal. Calcd for $\text{C}_{35}\text{H}_{53}\text{N}_7\text{O}_{18}\text{Cu}_2$: C, 42.59; H, 5.41; N, 9.93; found: C, 42.28; H, 5.34; N, 9.98. TGA data for loss of 5DMF and 5H₂O: calcd: 46.22%, found: 46.75%. IR (neat, cm⁻¹): 1652, 1625, 1591, 1442, 1381, 1362, 1247, 1091, 770, 755, 728, 659.

Single-crystal X-ray diffraction analysis revealed that UTSA-76 crystallizes in the R-3m space group. The framework was consistent with a paddlewheel dinuclear $\text{Cu}_2(\text{COO})_4$ secondary building units (SBUs) which are bridged by the carboxylates of L^{4-} to form a 3D NbO-type structure. There were two types of cages in the resulting framework. One small cage of about 10.5 Å in diameter is composed of 12 ligands connecting 6 paddlewheel SBUs. One of two nitrogen atoms in each ligand was directed towards this cage, which makes it contain a high density of Lewis basic sites. Another large irregular elongated cage consisted of 6 ligands connecting 12 paddlewheel SBUs. Similarly, this cage also has a high density of Lewis basic sites. Without wishing to be bound by any theory, these two cages with suitable pore sizes and high density of Lewis basic sites may play an important role for the methane storage. Table 1 shows crystallographic data shows structure refinement results for UTSA-76.

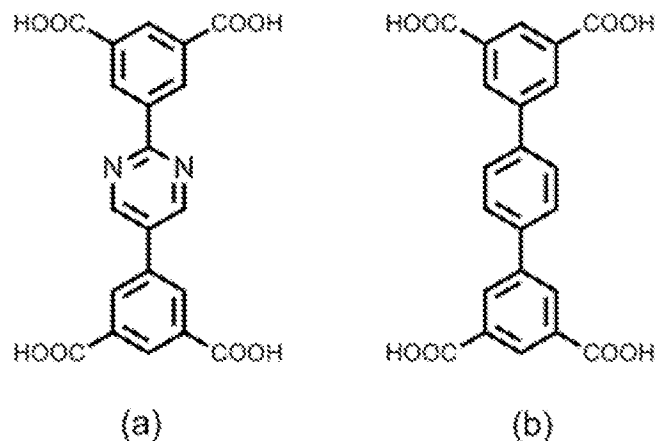
Table 1: Crystallographic data and structure refinement results for UTSA-76.

	UTSA-76
Formula	$\text{C}_{20}\text{H}_8\text{Cu}_2\text{N}_2\text{O}_{11}$
Formula weight	579.36
Temperature/K	100.00(19)
Crystal system	Trigonal
Space group	R-3m
<i>a</i> , <i>b</i> (Å)	18.6895(5)
<i>c</i> (Å)	37.6886(9)
<i>α</i> (°)	90.00
<i>β</i> (°)	90.00
<i>γ</i> (°)	120.00
<i>V</i> (Å ³)	11400.8(5)
<i>Z</i>	9
<i>D</i> _{calcd} (g cm ⁻³)	0.759
<i>μ</i> (mm ⁻¹)	0.868
<i>F</i> (000)	2592.0
Crystal size/mm ³	0.42 × 0.35 × 0.20
GOF	1.108
<i>R</i> _{int}	0.0338
<i>R</i> ₁ , <i>wR</i> ₂ [<i>I</i> ≥ 2σ (<i>I</i>)]	0.0808, 0.2558
<i>R</i> ₁ , <i>wR</i> ₂ [all data]	0.0896, 0.2627
Largest diff. peak and hole (e Å ⁻³)	1.12, -0.44

Example 3: Gas Absorption Properties of Metal Organic Frameworks

An organic linker containing pyrimidine group (Scheme 1) which was synthesized and structurally characterized its copper MOF $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2]\cdot 5\text{DMF}\cdot 3\text{H}_2\text{O}$ (described hereafter as UTSA-76). UTSA-76 is isostructural to NOTT-101, so these two MOFs have the comparable porosity and saturated methane storage capacities. However, UTSA-76 had much higher methane storage capacity than NOTT-101 at 65 bar and room temperature. UTSA-76 obtained a volumetric methane storage of $259\text{ cm}^3\text{ (STP) cm}^{-3}$ at 65 bar and room temperature. UTSA-76 had a working capacity of $199\text{ cm}^3\text{ (STP) cm}^{-3}$ at room temperature. Compared with HKUST-1 for methane storage, generally, UTSA-76 had a higher working capacity, but also exhibited a higher gravimetric energy density and gravimetric working capacity than HKUST-1.

SCHEME 1: Schematic structure of the organic ligands that serve as linkers in UTSA-76 (a) and NOTT-101 (b).



Acetone-exchanged UTSA-76 was activated at room temperature for 24 h, and then at 373 K under high vacuum to yield the activated UTSA-76. The porosity was characterized by nitrogen sorption at 77 K. The N_2 isotherm showed reversible Type-I sorption behavior, characteristic for the microporous materials with N_2 uptake of $698.2\text{ cm}^3\text{ g}^{-1}$ (FIG. 3). The Brunauer–Emmett–Teller (BET) surface area of UTSA-76 was $2820\text{ m}^2\text{ g}^{-1}$, and the pore volume calculated from the maximum amount of N_2 adsorbed was $1.092\text{ cm}^3\text{ g}^{-1}$, which are comparable to those of NOTT-101 (Table 1).

The high surface area, large pore volume, open copper sites and pyrimidine groups within the framework of UTSA-76 prompted examination of its capacity for high-pressure CH_4 storage. Temperature-dependent total methane sorption isotherms for UTSA-76 are shown in FIG. 4. At 125 K and 2.2 bar, the absolute methane adsorption of UTSA-76 reached $421.3\text{ cm}^3\text{ (STP) cm}^{-3}$ corresponding to an adsorbed methane density of 0.301 g cm^{-3} , which is 71.2 % of that of liquid methane (0.423 g cm^{-3}) at 113 K. UTSA-76 exhibited an absolute methane uptake

of $259 \text{ cm}^3 \text{ cm}^{-3}$ at 298 K and 65 bar, which almost meets the DOE target of 263 cm^3 (STP) cm^{-3} . Furthermore, the total gravimetric methane uptake of UTSA-76 was 0.264 g/g , which corresponds to 52.8% of the DOE's gravimetric target of 0.5 g/g .

HKUST-1 represents the standard for volumetric methane storage at room temperature and 65 bar with a volumetric methane storage of 267 cm^3 (STP) cm^{-3} and the methane storage of UTSA-76 was compared to HKUST-1. As shown in FIG. 4, the volumetric methane uptake of UTSA-76 was only slightly lower than HKUST-1, while the gravimetric uptake (0.264 g/g) was higher than HKUST-1 (0.216 g/g). Without wishing to be bound by any theory, the enhancement on the gravimetric methane uptake of UTSA-76 can be attributed to its larger surface area and pore volume compared with those of HKUST-1. Additionally, the methane uptake values of UTSA-76 and NOTT-101 were compared due to their similar structure (Table 2 and FIG. 5). It was found that both total volumetric and gravimetric methane uptakes of UTSA-76 are higher than those of NOTT-101 (FIG. 6). Without wishing to be bound by any theory, the pyrimidine groups in UTSA-76 are believed to be beneficial for its methane uptake.

Table 2: Comparison of some microporous MOFs for the high-pressure methane storage at room temperature and 65 bar.

MOFs	S_{BET}^a $\text{m}^2 \text{ g}^{-1}$	V_p^b $\text{cm}^3 \text{ g}^{-1}$	D_c^c g cm^{-3}	Total uptake ^d at 65 bar			Working capacity ^e at 65 bar		Initial Q_{st} kJ/mol
				g g^{-1}	$\text{cm}^3 \text{ cm}^{-3}$	density	g g^{-1}	$\text{cm}^3 \text{ cm}^{-3}$	
UTSA-76	2820	1.09	0.699	0.263	257	0.184	0.201	197	15.44
HKUST-1	1850	0.78	0.883	0.216	267	0.191	0.154	190	17
NOTT-101	2805	1.08	0.688	0.247	237	0.169	0.189	181	15.49

^aBET surface areas calculated from N_2 isotherms at 77 K. ^bPore volumes calculated from the maximum amounts of N_2 adsorbed. ^cFramework densities without guest molecules and terminal waters. ^dAt 298 K and 65 bar. ^eDefined as the difference of the amount of methane adsorbed between 65 bar and 5 bar.

Additionally, the working capacity or deliverable capacity determines the driving range of natural gas vehicles (NGVs) and should be evaluated to determine a material's performance. The working capacity is defined here as the difference of the amount of methane adsorbed between 65 bar and 5 bar. For example, a good methane storage material should have a high methane uptake at 65 bar but a low uptake at 5 bar. From Table 1, UTSA-76 exhibited an working capacity of 199 cm^3 (STP) cm^{-3} , which is $\sim 5\%$ higher than HKUST-1 (190 cm^3 (STP) cm^{-3}). This working capacity of UTSA-76 was found to be primarily due to its much lower methane uptake at 5 bar (FIG. 7). The relatively low methane uptake in UTSA-76 at low pressure was attributed to its lower initial Q_{st} of CH_4 adsorption compared to that of HKUST-1 (Table 1). Furthermore, the gravimetric working capacity of UTSA-76 (0.202 g/g) was higher than that of HKUST-1 (0.154 g/g) mainly due to its comparatively higher gravimetric uptake at

65 bar. In contrast to UTSA-76, the isostructural NOTT-101 showed a lower volumetric working capacity than HKUST-1 ($181 \text{ cm}^3 \text{ (STP) cm}^{-3}$ vs. $190 \text{ cm}^3 \text{ (STP) cm}^{-3}$).

The different methane storage performances including the working capacity, the total volumetric and gravimetric uptakes between UTSA-76 and NOTT-101 motivated exploration into why the introduction of pyrimidine groups can result in an increase in methane storage.

To investigate the improved methane storage performance of UTSA-76 was compared to NOTT-101, the two MOFs were examined from structural perspective. Experimental x-ray diffraction data showed that the two MOFs are isostructural with same crystal symmetry (R-3m). Lattice parameters of the fully activated samples were close, with a being almost identical and c differing by $\sim 1.2\%$ (**FIGS. 8 and 9**). Consequently, the theoretical crystal densities, pore volumes, surface areas of the two were similar. Introducing pyrimidine groups to the linker did not alter the overall MOF pore structure, and the difference in methane adsorption of the two MOFs was not due to a change in pore geometry. Both of our UTSA-76 and NOTT-101 samples are highly crystalline, and the experimental pore volumes obtained from 77K N_2 adsorption data are comparable to their corresponding theoretical pore volumes, the methane adsorption capacity difference was not from sample quality variation (**FIG. 10**). The possibility of amount of structural vacancies present in the MOF samples was also be ruled out, since no monocarboxylate modulator or co-assembler (which was known to promote linker vacancies) was used in either NOTT-101 or UTSA-76 synthesis (Park *et al.*, 2012 and Wu *et al.*, 2013). The reported volumetric uptake values were converted from the experimental gravimetric uptake values using the ideal crystal densities. The volumetric uptake values (different by $\sim 9\%$) can be affected by the deviation of the true crystal densities, however, gravimetric uptakes are reliable since the gravimetric uptakes are obtained via measurement. The $\sim 7\%$ difference between the two MOFs' gravimetric methane uptake suggested, without wishing to be bound by any theory, that the improved methane storage performance of UTSA-76 has a structural origin.

The adsorption energy of CH_4 was explored as a possible reason for the methane adsorption isotherm difference. First-principles DFT-D (dispersion-corrected density-functional theory) calculations were carried out, where van der Waals (vdW) interactions were corrected by empirical r-6 terms (Giannozzi *et al.*, 2009). Structural optimizations were first performed on UTSA-76 and NOTT-101 structures. The relaxed static structures of the two were similar. CH_4 molecules were introduced into the MOF structures. For other Cu-MOFs with similar crystal structures, the previous combined neutron diffraction, GCMC and DFT studies have shown that the open Cu sites and cage window sites are the two primary CH_4 adsorptions sites (Wu *et al.*, 2010). For UTSA-76 and NOTT-101, these major CH_4 adsorptions sites are the same. Adsorption of methane on the linker surfaces are generally weaker secondary adsorption. The

calculations showed that CH₄ molecules adsorbed next to the pyrimidine sites of UTSA-76 exhibited similar binding energies as those adsorbed on the central phenyl ring of NOTT-101. No new adsorption sites were found in UTSA-76 introduced by the pyrimidine sites. For static structures of the two MOFs, without wishing to be bound by any theory, the calculated
5 adsorption affinity on the linker pore surface were similar and likely not the reason for the different methane storage performance.

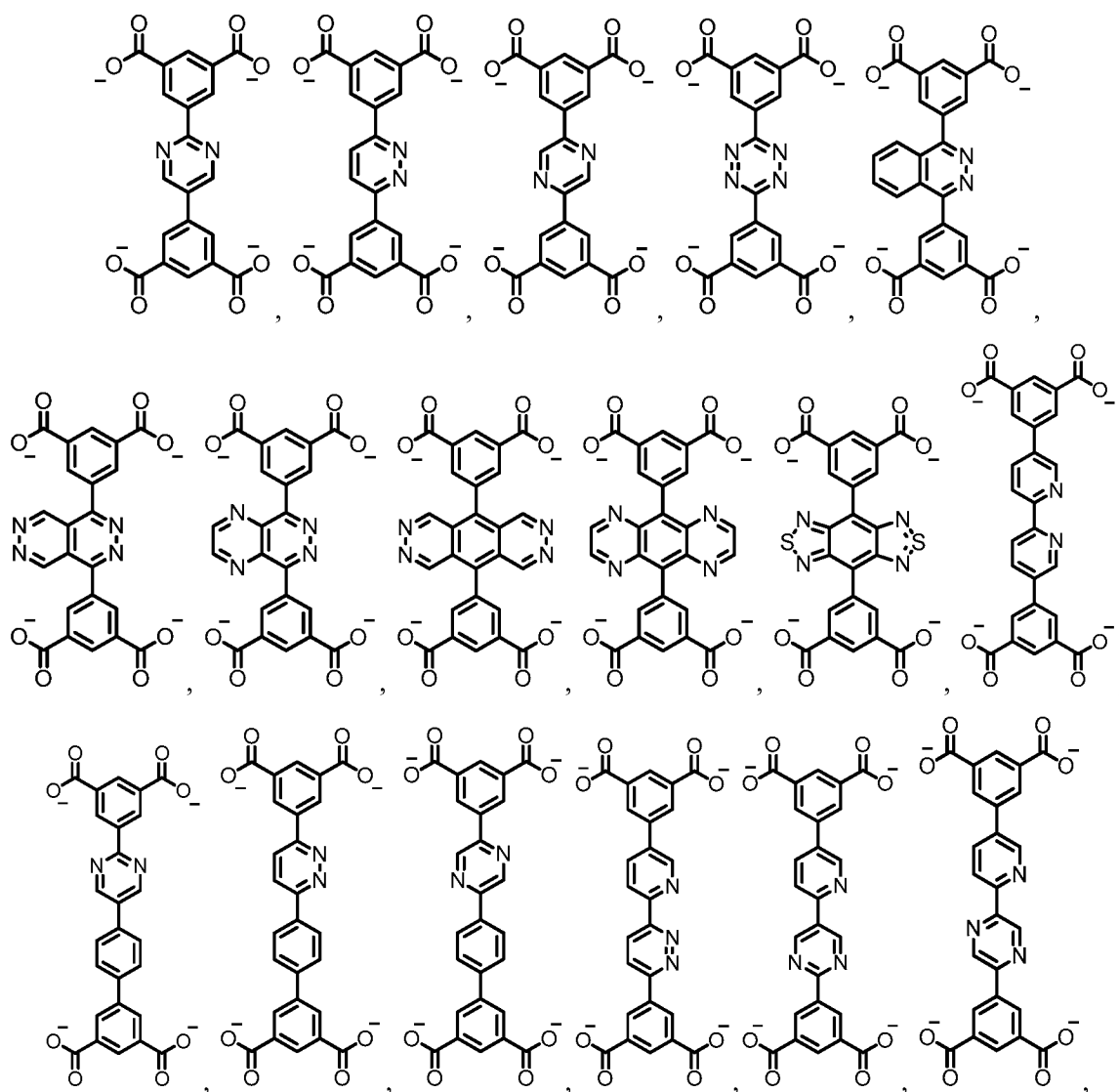
Similar to other non-flexible Cu-MOFs, NOTT-101 and UTSA-76 have relatively rigid framework structures and, without wishing to be bound by theory, the crystal structures often remain generally unchanged upon gas adsorption/desorption in contrast to highly flexible MOFs.
10 Without wishing to be bound by any theory, the central rings of the linkers had relatively large rotational freedom, which may affect methane storage to certain extent. The energy cost of a rotational motion around two equivalent orientations of the central rings was calculated. The UTSA-76 linker central ring was found to have a shallower rotational barrier (~8.2 kJ/mol vs. ~20.2 kJ/mol, **FIG. 11**), and thus was significantly more “flexible” than the NOTT-101 linker
15 central ring. As a reference, the calculated rotational barrier for the π -flipping of the benzene group in the well-studied MOF-5 was significantly higher, ~55 kJ/mol (Zhou and Yildirim, 2006). Upon methane adsorption at room temperature, without wishing to be bound by any theory, the central rings of UTSA-76 may adjust their orientations in a harmonic way, to maximize the methane-framework interactions and accommodate more methane molecules.

20 To experimentally confirm the central linker ring in UTSA-76 had higher rotational freedom, neutron scattering measurements were performed. Neutron scattering is dominated by incoherent scattering from hydrogen atoms. For both UTSA-76 and NOTT-101, the H atoms on the phenyl rings of both end of the linker typically do not have additional movement except thermal motion, because of the restriction of the two carboxylate linkage to the metal centers. In
25 contrast, the H atoms on the central rings have additional motions such as but not limited to librations, two-site jumping, or π -flipping of the central ring. Neutron scattering was used to probe the H motion on the central rings of the MOF linker. Elastic scans of the neutron scattering intensity vs. temperature for UTSA-76 and NOTT-101 were conducted, from which, the temperature-dependent atomic mean-square displacements were derived (**FIG. 12**). The
30 rotational motion of the UTSA-76 central ring was found to enter the time scale window accessible by the spectrometer ($\sim 10^{-8}$ s) at much lower temperature than the NOTT-101 central ring (~70 K vs. ~150 K). These data showed that the UTSA-76 central ring indeed has higher mobility than NOTT-101, which agreed with the DFT calculations that suggest a much lower rotational barrier for NOTT-101.

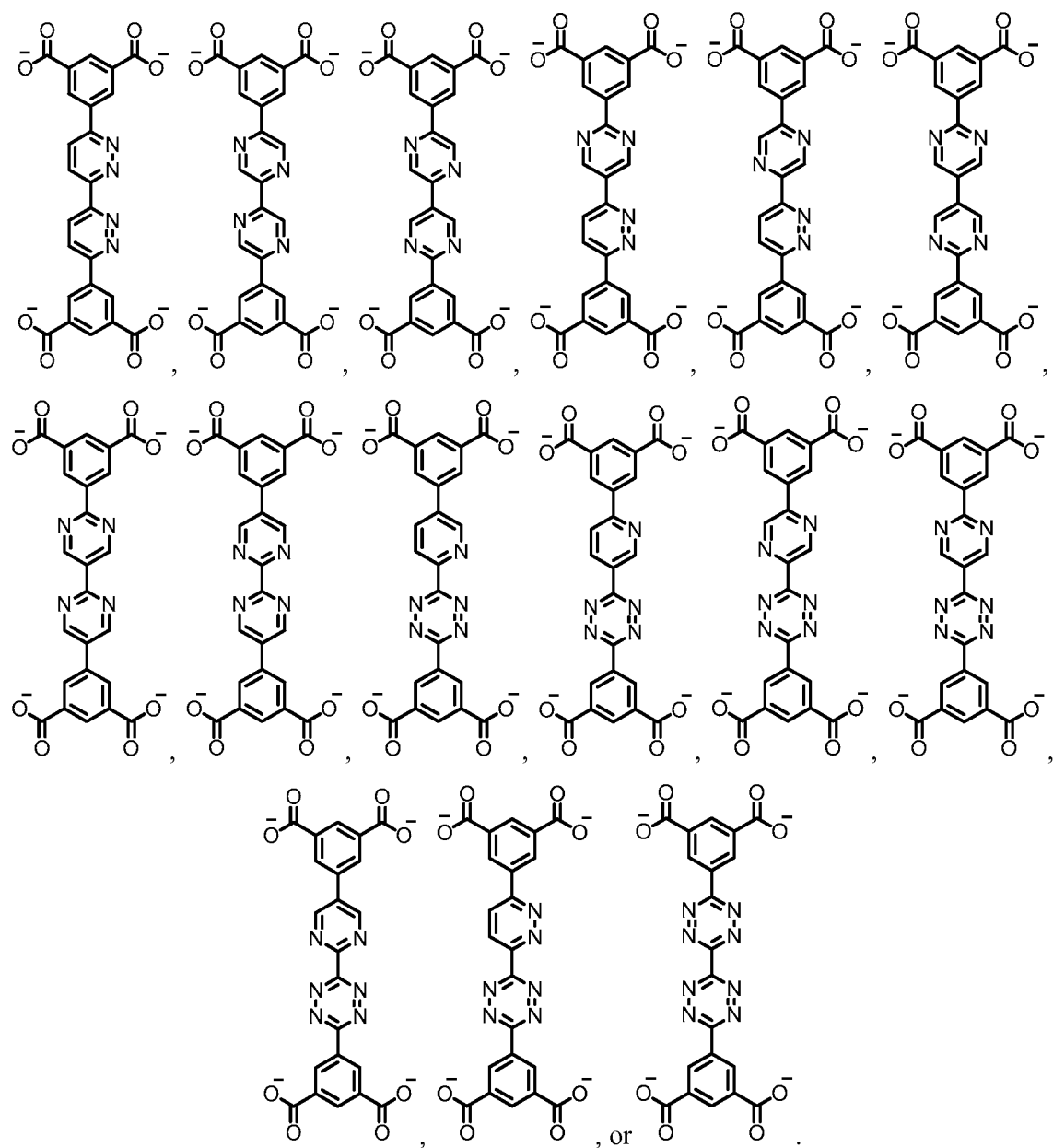
Without being bound by theory, the higher central ring rotational freedom is believed to likely be responsible for the enhanced methane storage performance of UTSA-76. This observation was in line with the fact that the experimental Q_{st} of methane adsorption in the two MOFs are quite close, with $Q_{st}(\text{UTSA-76})$ being only slightly higher than $Q_{st}(\text{NOTT-101})$ at high methane loading (FIGS. 13-15).

Example 4: Additional Ligands

In some embodiments, the invention provides MOFs based on one or more of the ligands having the formulas listed below, or partially or completely protonated forms thereof:



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REFERENCES

The following references, to the extent that they provide exemplary procedural or other details supplementary to those set forth herein, are specifically incorporated herein by reference.

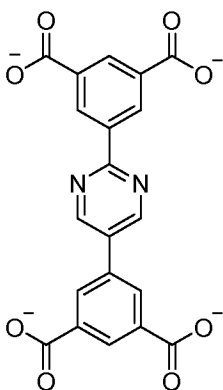
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CLAIMS

WHAT IS CLAIMED IS:

1. A metal-organic framework (MOF) comprising a repeat unit of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2]$, wherein L is a ligand of the formula:



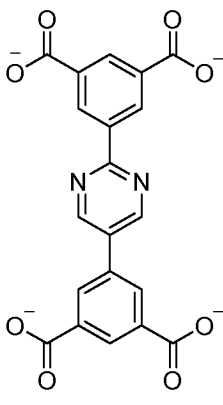
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2. The MOF of claim 1, wherein the MOF is activated for sorption of gas molecules.
3. The MOF of claim 1, further comprising one or more than one type of guest molecule.
4. The MOF of claim 3, wherein one type of guest molecule is a solvent molecule.
5. The MOF of claim 4, wherein the solvent molecule is water.
- 10 6. The MOF of claim 4, wherein the solvent molecule is *N,N'*-dimethylformamide.
7. The MOF of claim 1, further comprising about five *N,N'*-dimethylformamide and three water molecules per repeat unit.
8. The MOF of claim 7, wherein the repeating formula is further defined as $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$.
- 15 9. The MOF of claim 1, wherein the solvent molecules occupy the pores of the MOF.
10. The MOF of claim 3, wherein one type of guest molecule is a gas molecule.
11. The MOF of claim 10, wherein the gas molecule is H_2 , CO_2 , or CH_4 .
12. The MOF of claim 11, wherein the gas molecule is CO_2 .
13. The MOF of claim 11; wherein the gas molecule is CH_4 .
- 20 14. The MOF of claim 11; wherein the gas molecule is H_2 .
15. The MOF of claim 11, wherein the gas molecule is CO_2 and CH_4 .
16. The MOF of claim 1, wherein the MOF is substantially free from any solvent molecules.

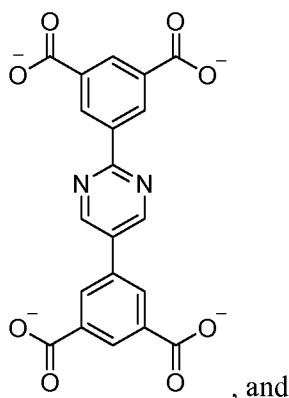
17. The MOF of claim 1, having a weight percentage at least 90% attributable to repeat units of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$.
18. The MOF of claim 1, having a weight percentage at least 95% attributable to repeat units of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$.
- 5 19. The MOF of claim 1, having a weight percentage at least 99% attributable to repeat units of the formula $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$.
20. The MOF of claim 1, wherein the MOF has been adhered to a fixed surface.
21. A method of separating two or more compounds using an MOF comprising:
 - (a) obtaining a MOF comprising a repeat unit of the formula

10

 $[\text{Cu}_2\text{L}(\text{H}_2\text{O})_2] \cdot 5\text{DMF} \cdot 3\text{H}_2\text{O}$, wherein L is a ligand of formula:



, and



- (b) combining the MOF with a mixture comprising a first compound and a second compound; and
- (c) separating the first compound from the second compound.
- 15 22. The method of claim 21, wherein the MOF is activated for sorption of gas molecules.
23. The method of claim 21, wherein the separation is based on their differential sorption rate within the MOF.
24. The method of claim 21, wherein the first compound is a gas molecule.
25. The method of claim 24, wherein the first compound is H_2 .
- 20 26. The method of claim 21, wherein the second compound is a gas molecule.
27. The method of claim 26, wherein the second compound is CH_4 or CO_2 .
28. The method of claim 26, wherein the second compound is CH_4 .
29. The method of claim 26, wherein the second compound is CO_2 .

30. The method of claim 21, wherein the mixture further comprises a third compound.
31. The method of claim 30, wherein the third compound is CH₄.
32. The method of claim 30, wherein the third compound is CO₂.
33. The method of claim 28, wherein the mixture comprises H₂ and CH₄.
- 5 34. The method of claim 29, wherein the mixture comprises H₂ and CO₂.
35. The method of claim 30, wherein the mixture comprises H₂, CH₄, and CO₂.
36. The method of claim 21, wherein the separation is carried out at a pressure from about 10 kPa to about 50 mPa.
37. The method of claim 36, wherein the separation is carried out at a pressure from about 2
10 mPa to about 20 mPa.
38. The method of claim 37, wherein the separation is carried out at a pressure from about 4 mPa to about 15 mPa.
39. The method of claim 21, wherein the MOF is adhered to a fixed bed surface.
40. The method of claim 21, wherein the MOF is packed in an absorber.
- 15 41. The method of claim 21, wherein the absorption is carried out at a temperature from about -50 °C to about 50 °C.
42. A method of using a metal organic framework (MOF), wherein the MOF is an MOF according to any one of claims 1-20 and the MOF is used in an application selected from sensing, heterogeneous catalysis, drug delivery, lithium sulfide battery, membranes, and
20 analytical devices.

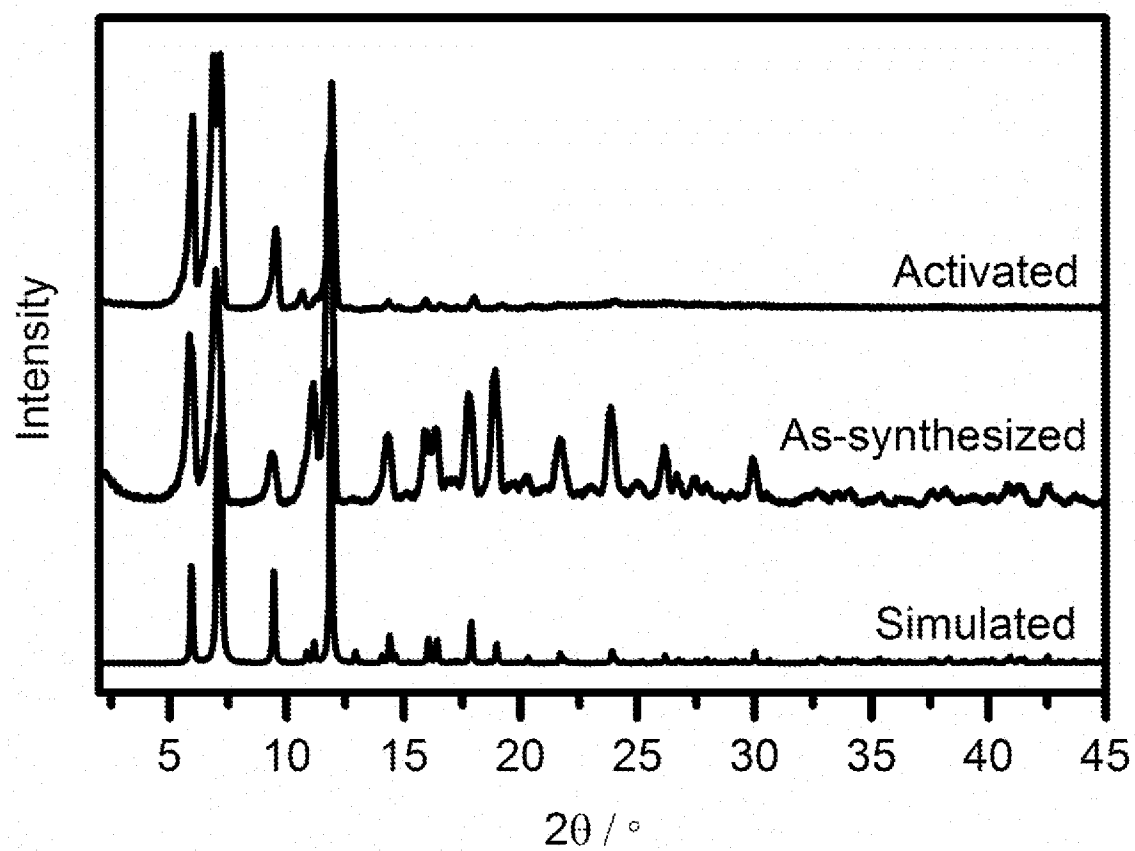


FIG. 1

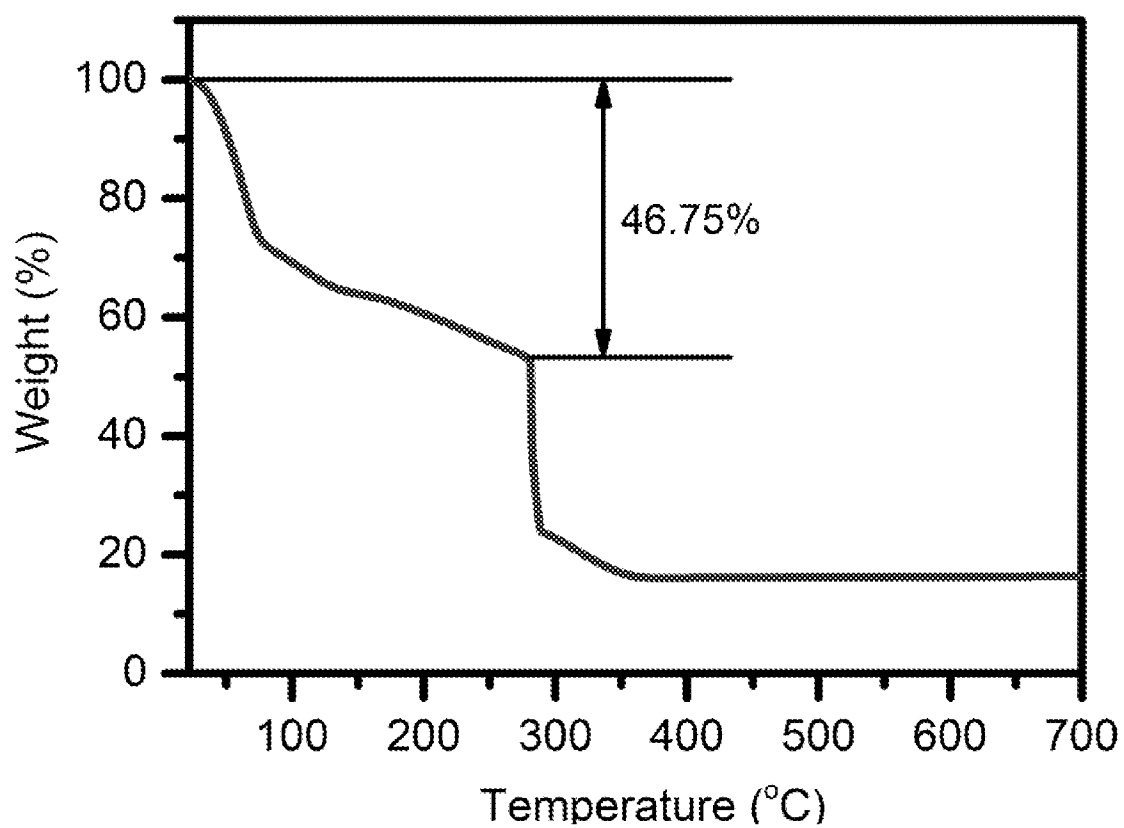


FIG. 2

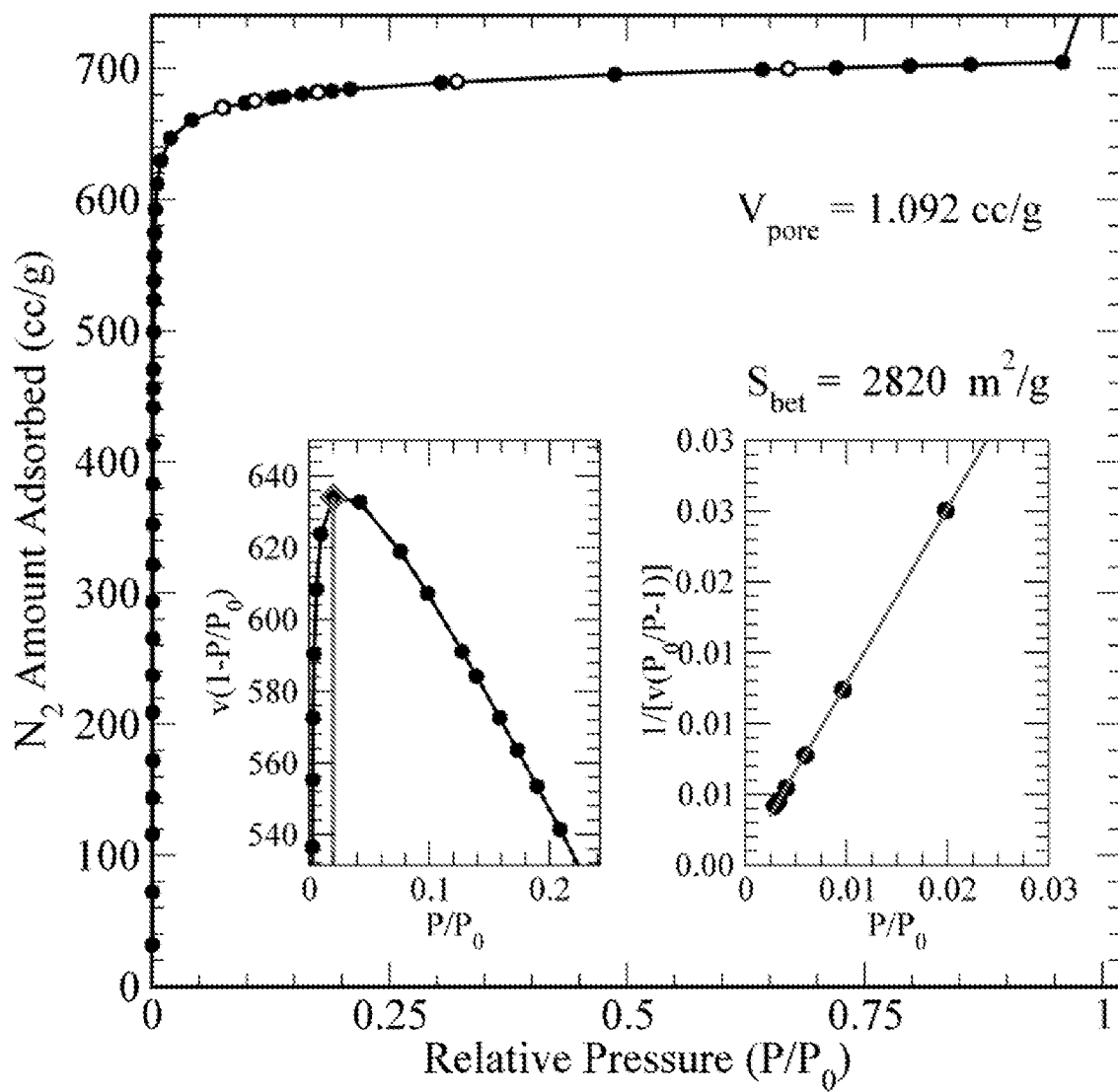


FIG. 3

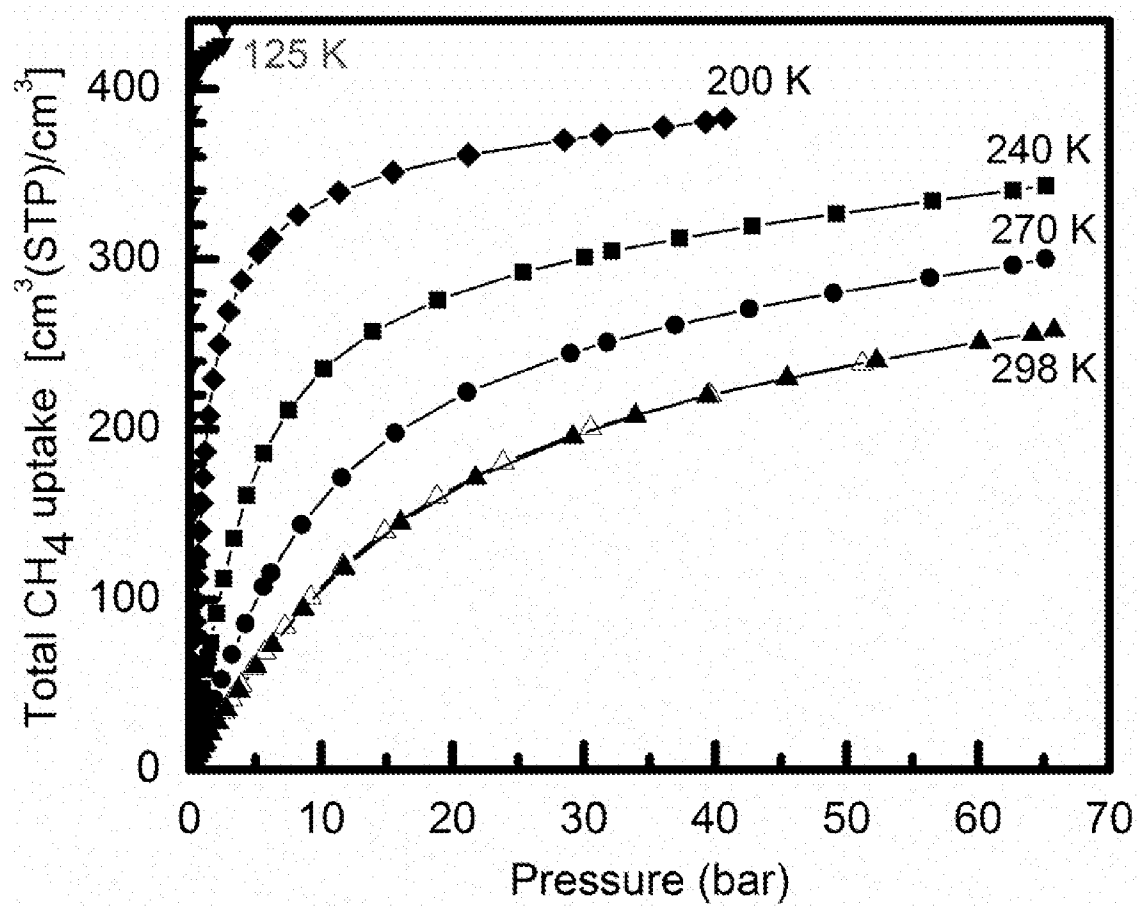


FIG. 4

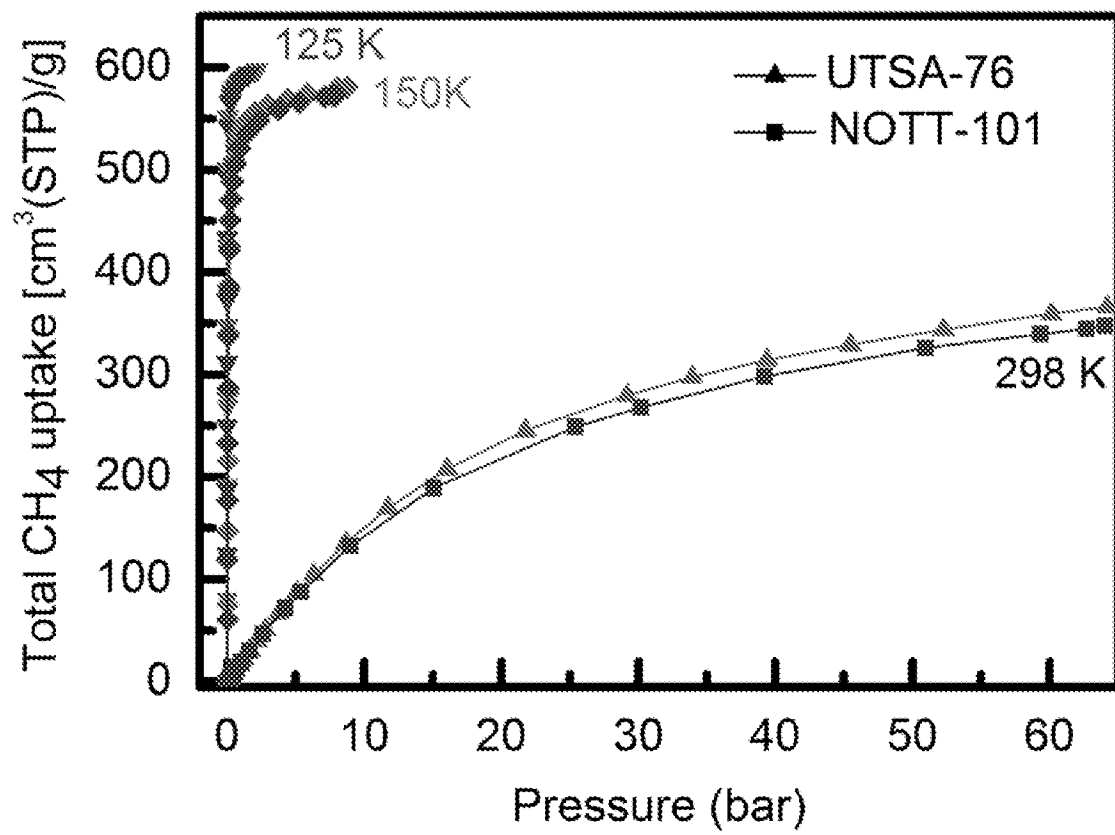


FIG. 5

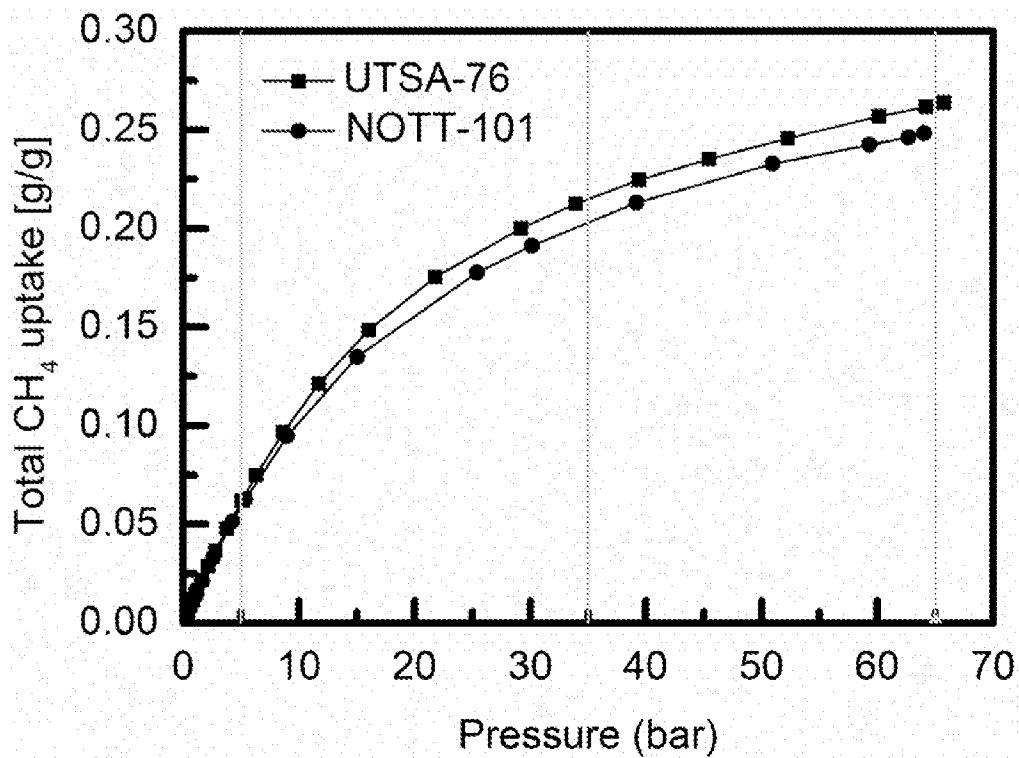
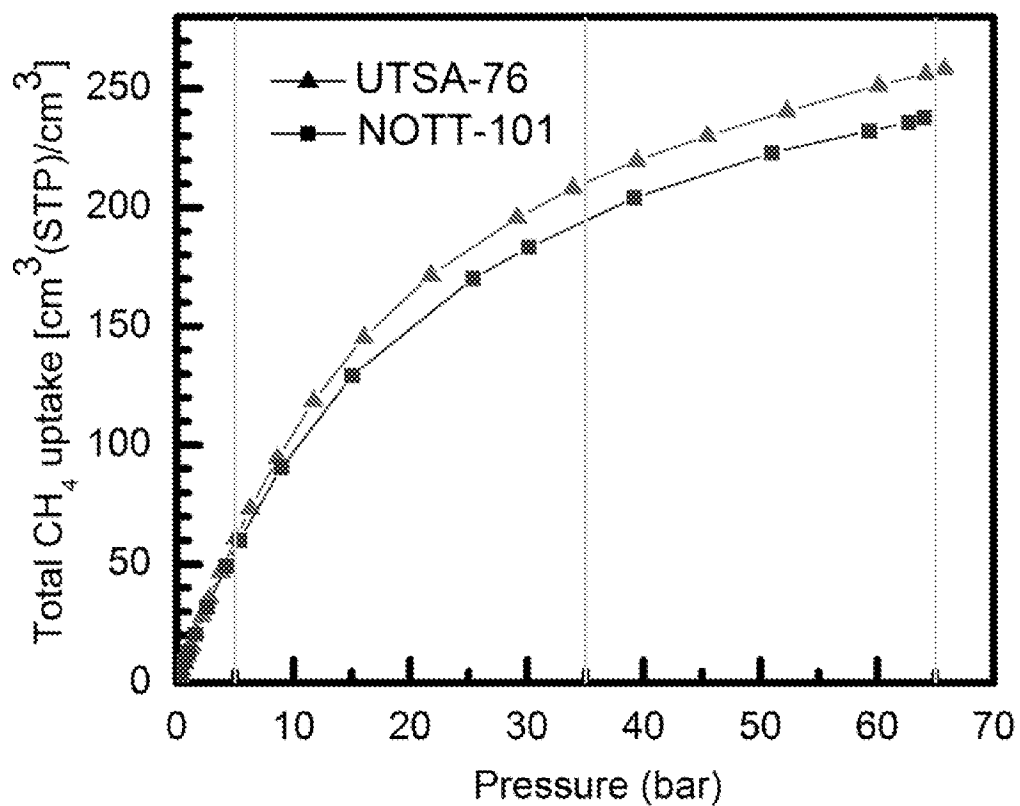


FIG. 6

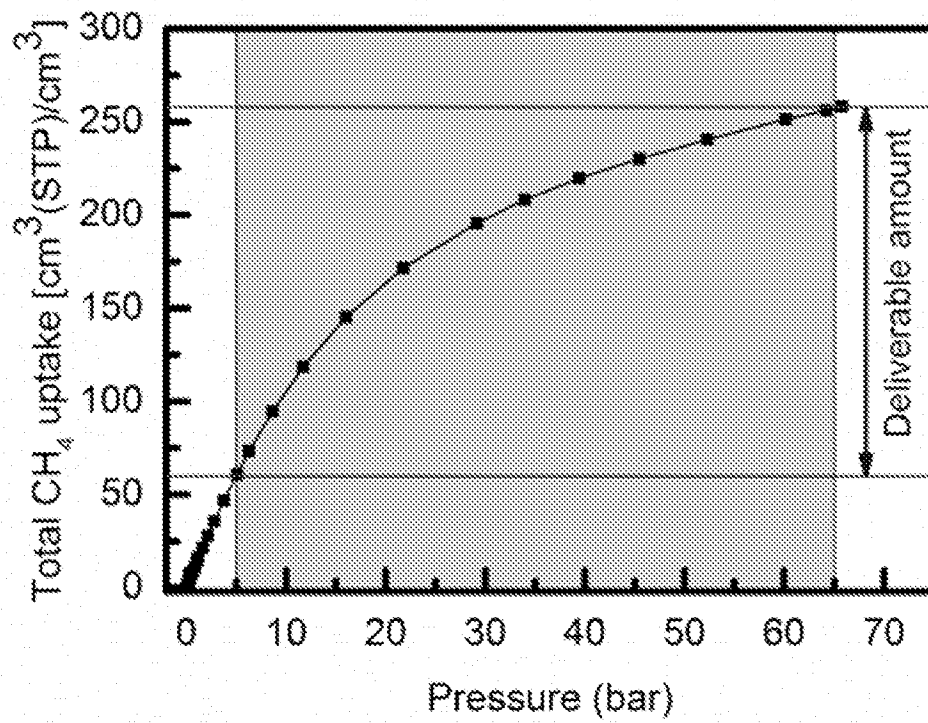


FIG. 7

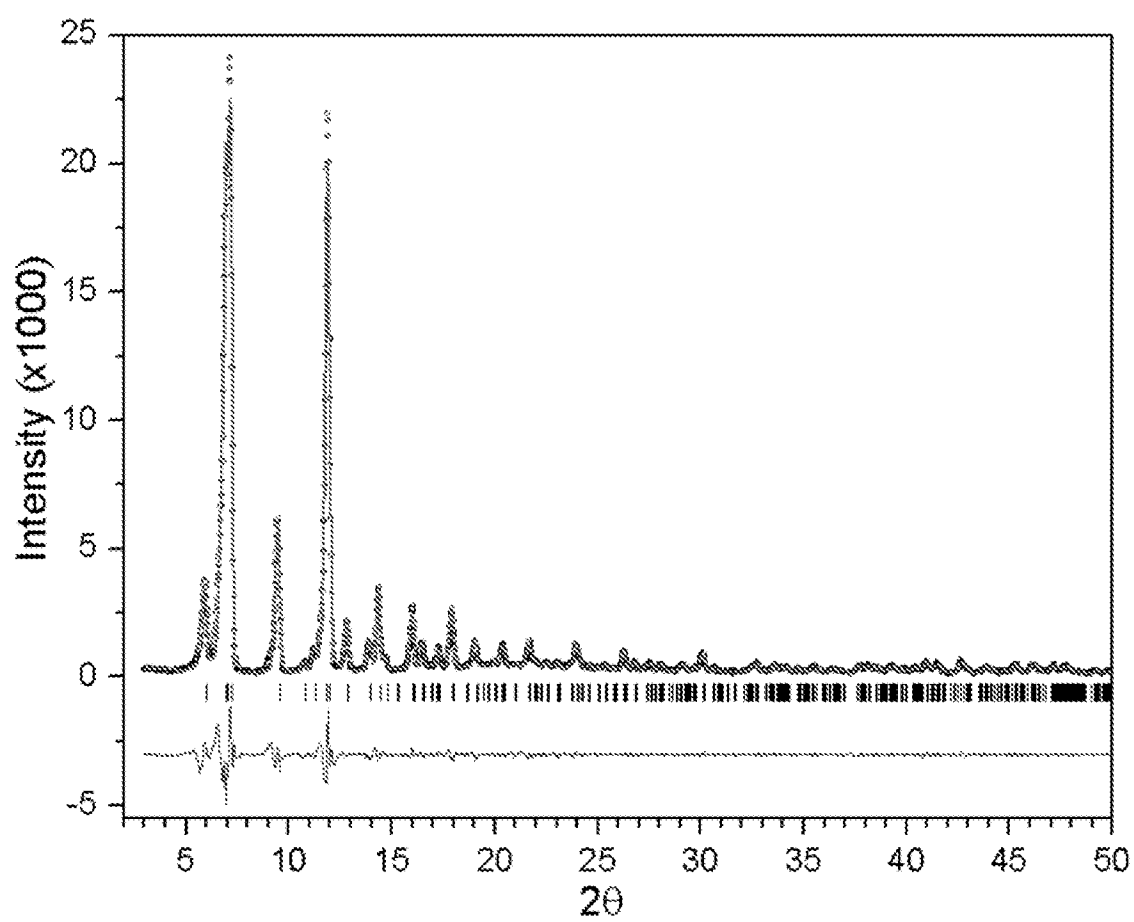


FIG. 8

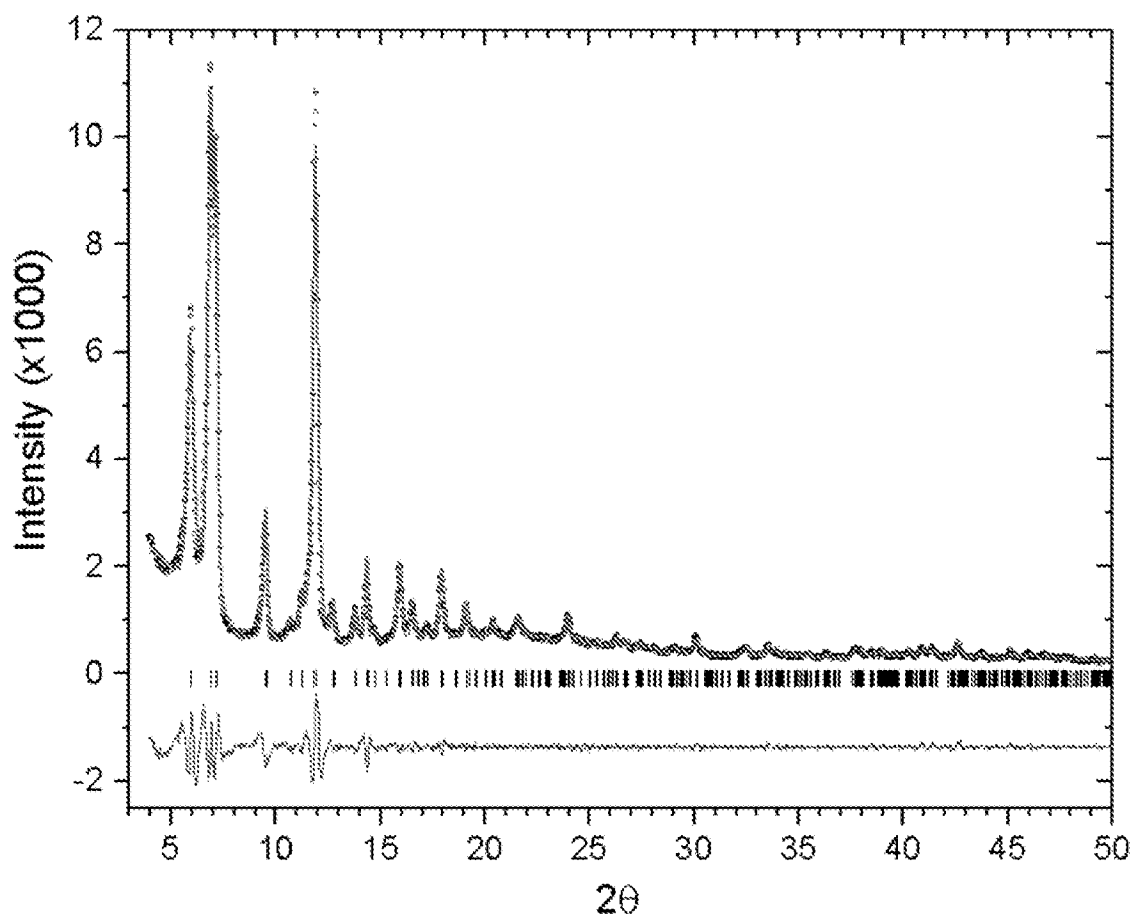


FIG. 9

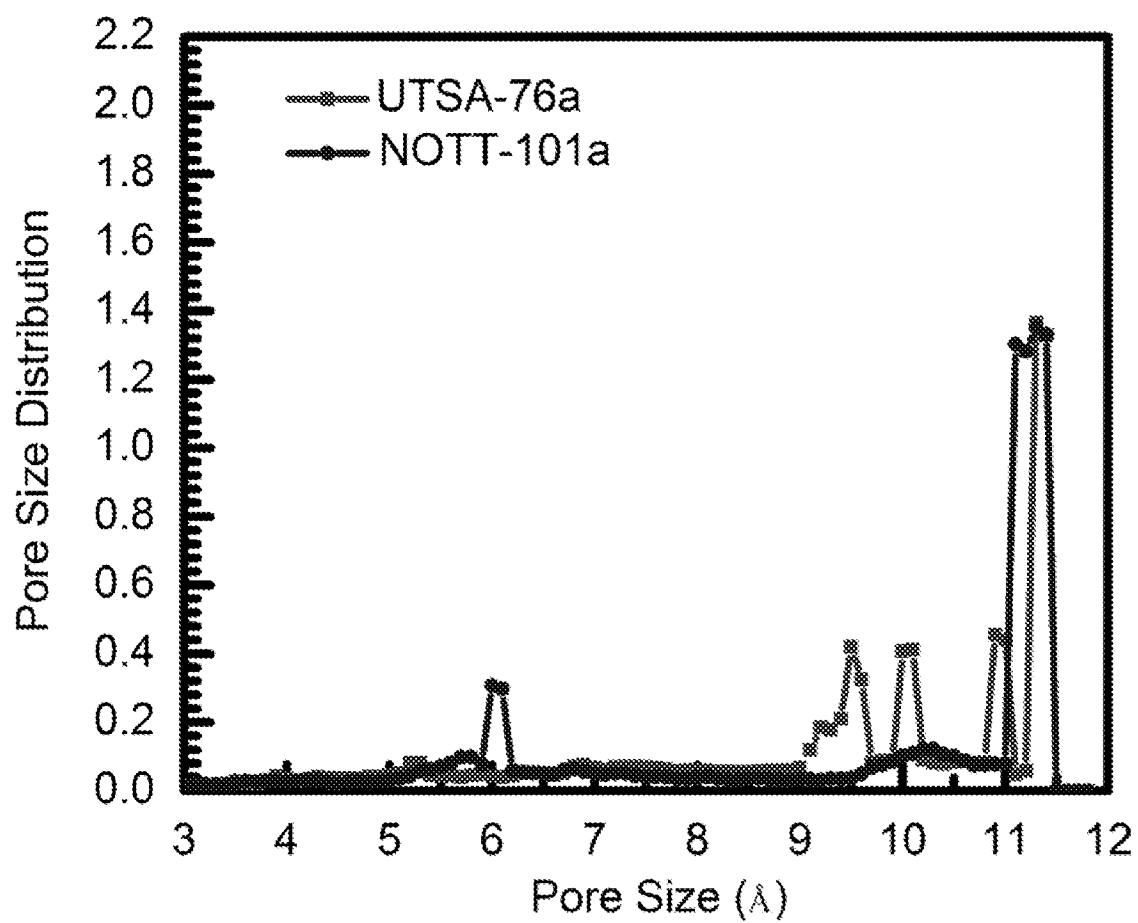


FIG. 10

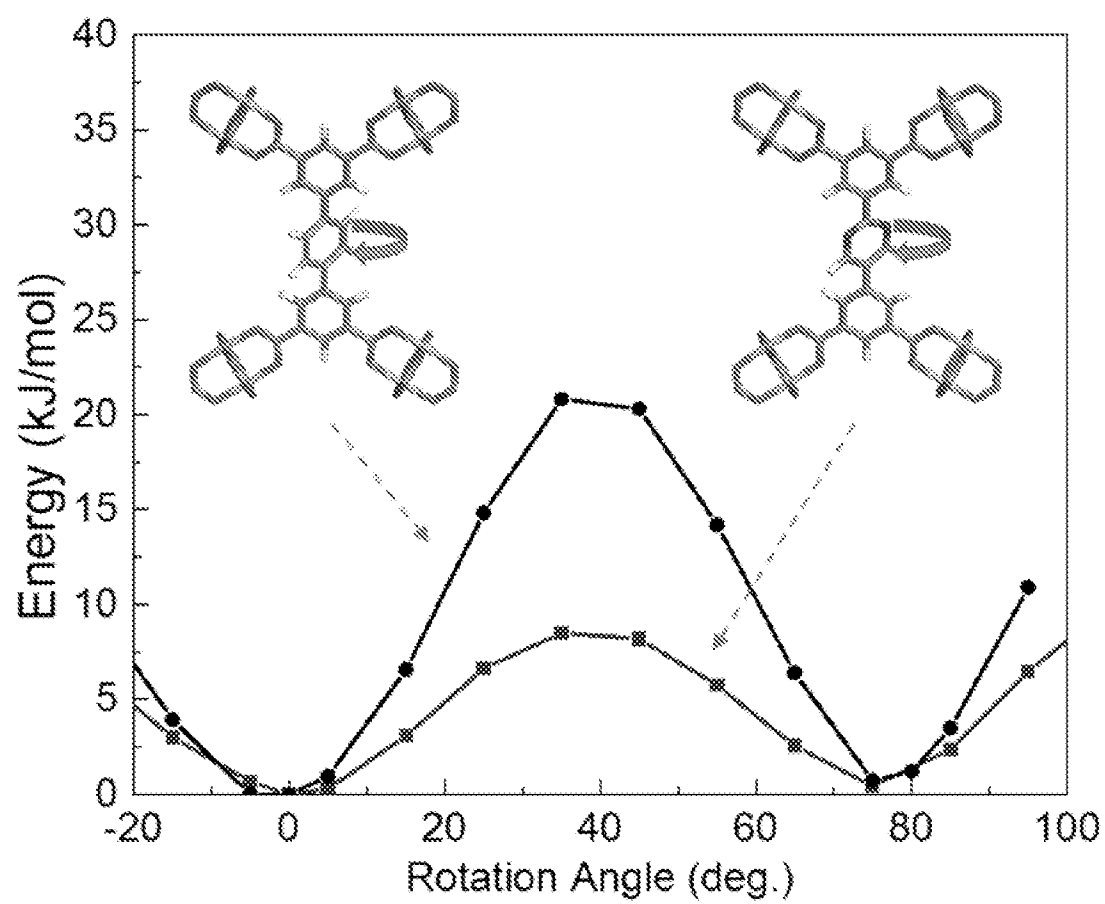


FIG. 11

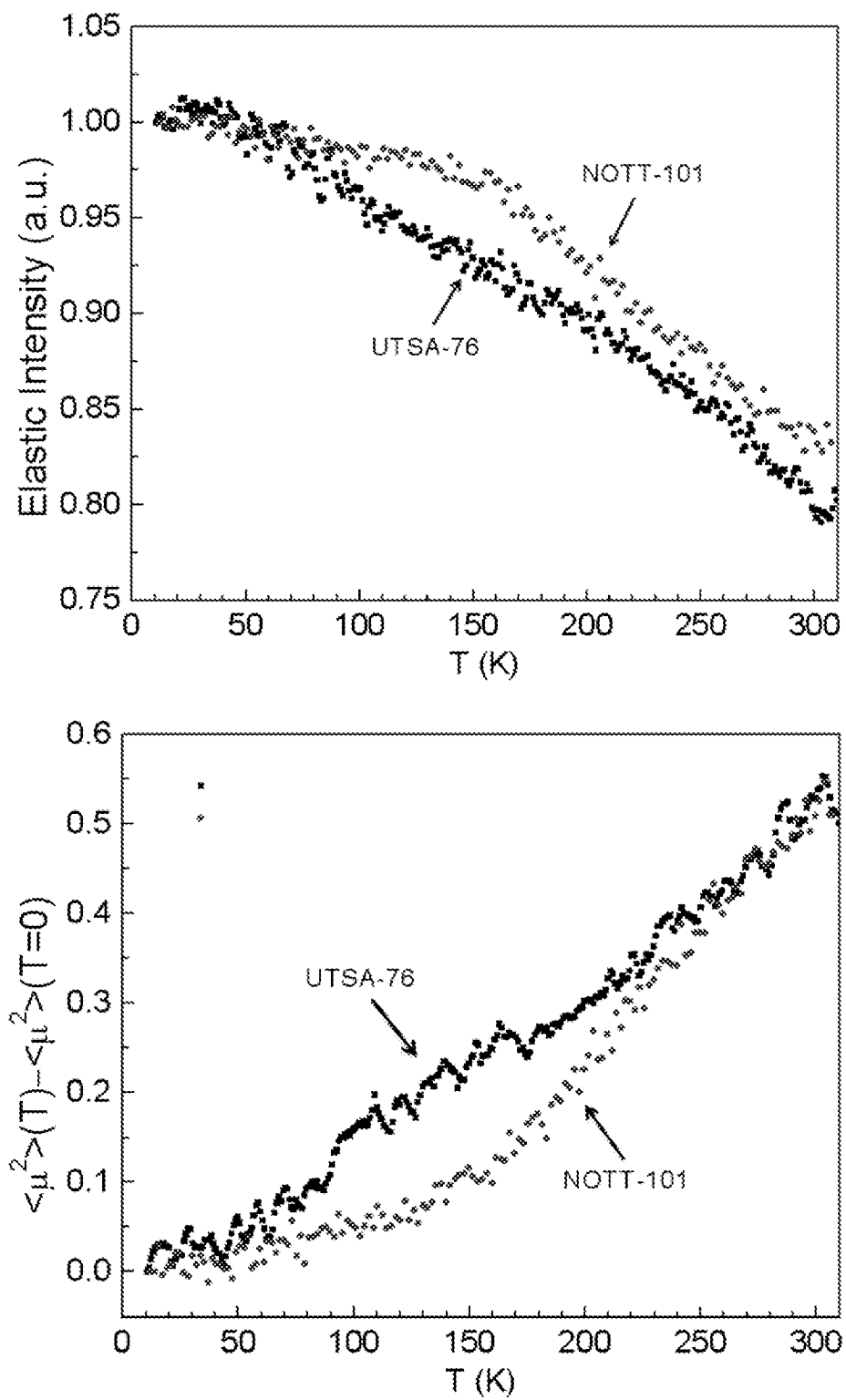


FIG. 12

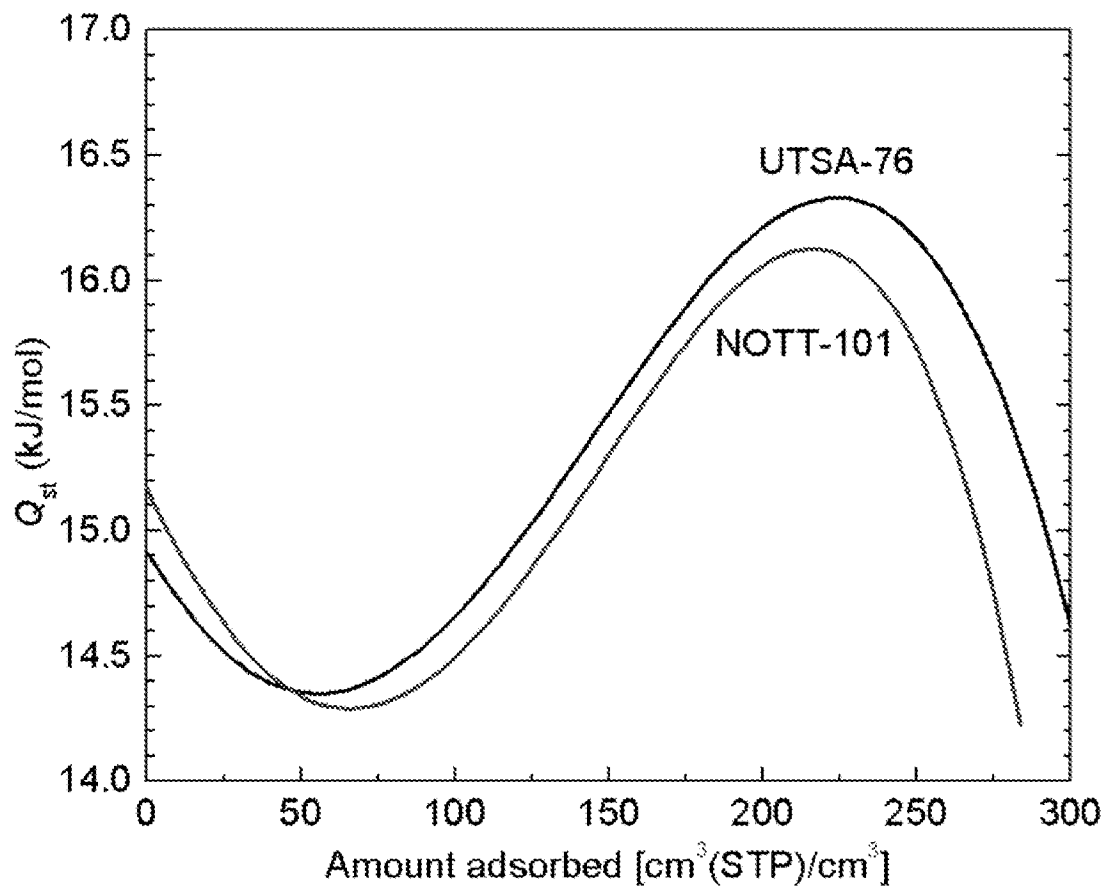


FIG. 13

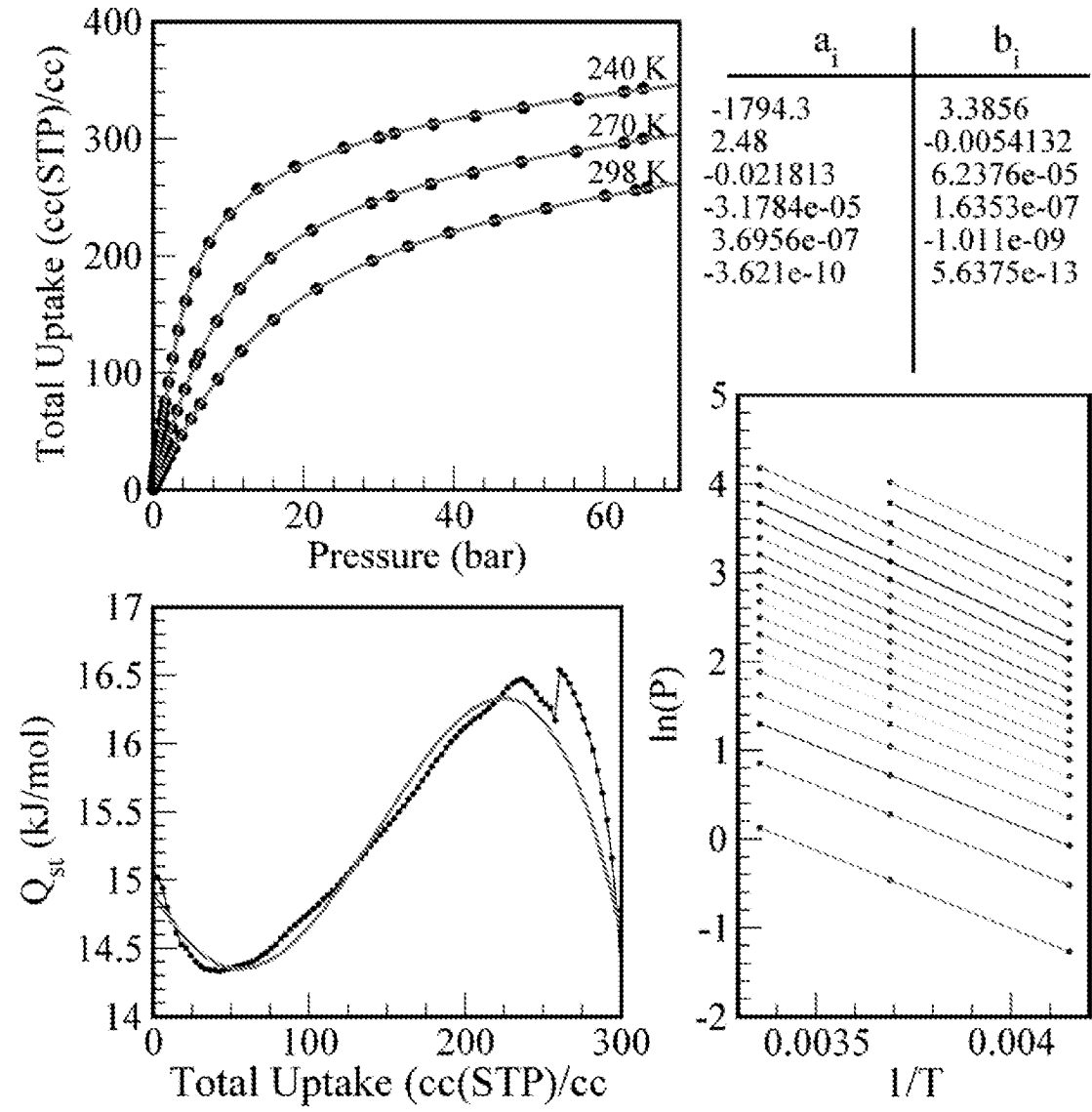


FIG. 14

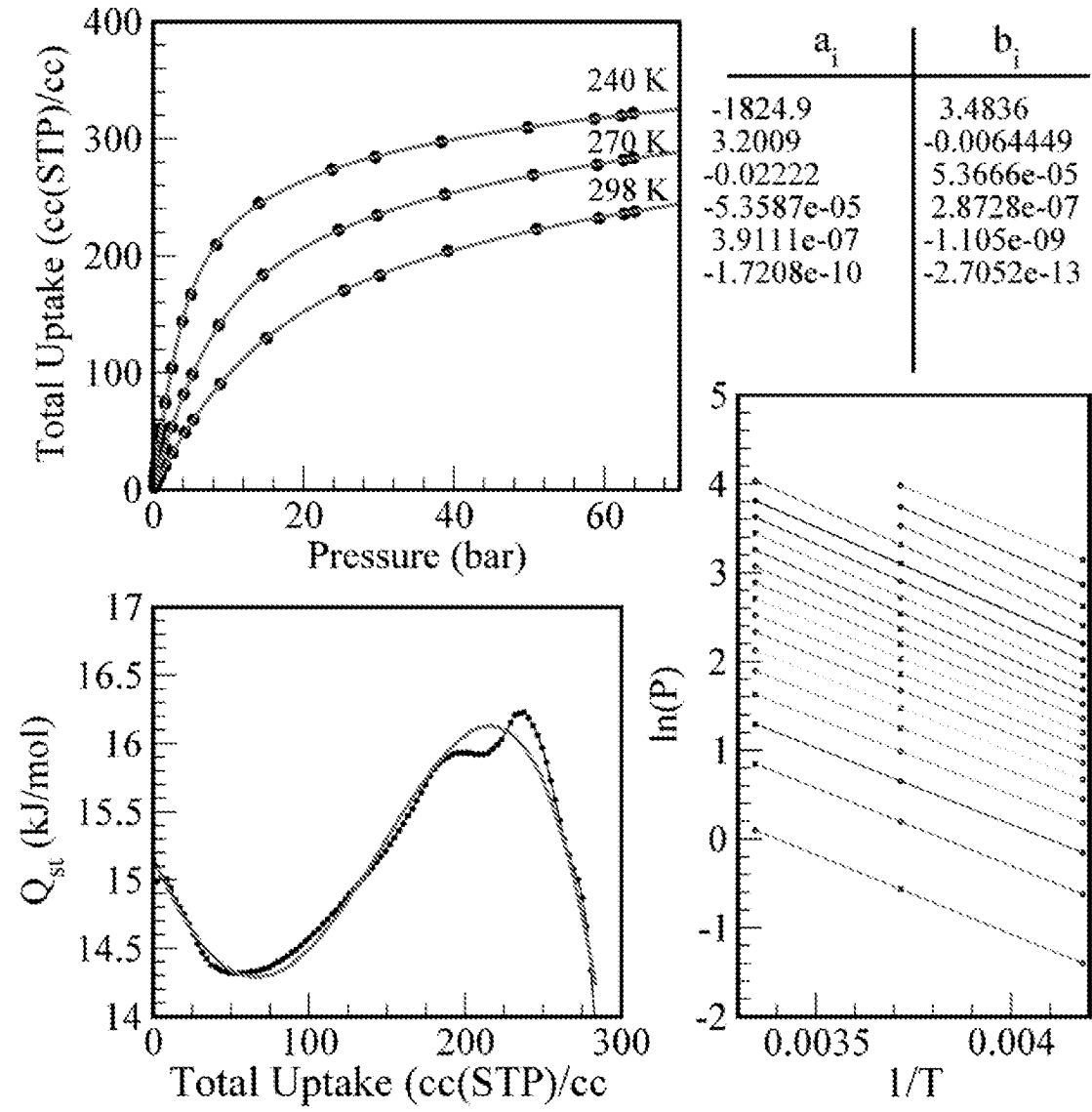


FIG. 15

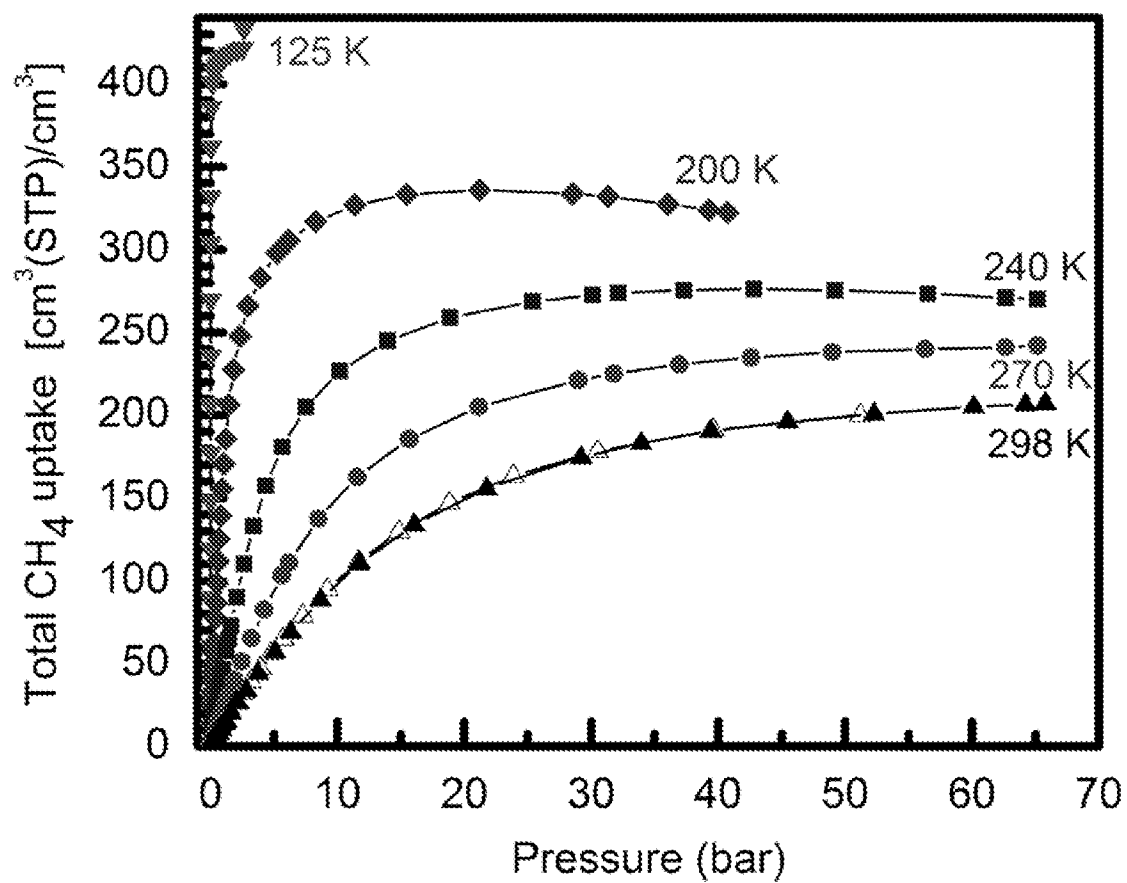


FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/21691

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B01J31/22 (2015.01)

CPC - B01J20/226

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - B01J31/22, 20/30 (2015.01)

CPC - B01J20/226; B01D53/02, 2253/306; Y02C10/08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); ProQuest; Ebsco; Google; Google Scholar; SureChem; PubMed; PubChem; metal-organic framework; Cu₂L(H₂O)₂; sorption; differential gass sorption; hydrogen; methane; carbon dioxide

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,648,508 A (YAGHI, OM) 15 July 1997; abstract; column 4, lines 39-53; column 5, line 60 to column 6, line 20.	1-41, 42/1-20
A	US 2012/0172612 A1 (YAGHI, OM et al.) 05 July 2012; paragraphs [0004]-[0007].	1-41, 42/1-20
A	WILMER, CE et al. 'Large-scale screening of hypothetical metal-organic frameworks'. Nature Chemistry, February 2011, Vol. 4, pages 83-89; abstract; figure 3; page 86.	1-41, 42/1-20
A	FURUKAWA, H et al. 'The Chemistry and Application of Metal-Organic Frameworks'. Science, August 2013, Vol. 341, page 974.	1-41, 42/1-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

20 May 2015 (20.05.2015)

Date of mailing of the international search report

17 JUN 2015

Name and mailing address of the ISA/

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