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Evaluation of adsorption properties of a porous carbon material from coffee waste

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Abstract: The article investigates and evaluates the adsorption properties of a new highly porous carbon material in a wide range of pressures at temperatures above the critical level. It has been shown that the activated carbon material obtained from coffee waste is an effective adsorbent for CH_4. So, in this study, carbonized coffee grounds were used as a precursor to obtain a highly porous carbon material (HPCM5), by chemical activation at 750 °C for efficient CH_4 adsorption. Porometry shows that the obtained adsorbent is micromesoporous with a narrow pore size distribution, having a BET specific surface area of 3456 $m^2 \cdot g^{-1}$ and a pore volume of 1.604 $cm^3 \cdot g^{-1}$. The adsorption of CH_4 on the resulting carbon material was studied at temperatures of 298.15–323.15 K and pressures up to 100 bar. HPCM5 demonstrates a high CH_4 adsorption capacity of 19 $mmol \cdot g^{-1}$ at 10 MPa and 298.15 K. Experimental data on CH_4 adsorption on HPCM5 were analyzed using typical Langmuir and Freundlich adsorption models in the temperature range 298.15–323.13 K. The results show that CH_4 adsorption on HPCM5 in the range of temperatures and pressures considered in this study correspond to the Langmuir adsorption; this is confirmed by the obtained values of the correlation coefficients equal to 0.99 and the average relative deviations between the experimental results and the results obtained with the Langmuir model, which are less than 3 %. The values of isosteric heats were calculated for different absolute amounts of CH_4 adsorption on the resulting HPCM5, which are in the range from ~10.0 to 17.0 $kJ \cdot mol^{-1}$. This characterizes the process as a physical adsorption, and the bond strength between the CH_4 molecule and adsorbent surface refers to the van der Waals force. The adsorption isotherm data and thermodynamic parameters evaluated in this study are useful for designing adsorption-based gas storage systems.

Keywords: adsorption; carbon adsorbent; methane; adsorption isotherms; adsorption isosteres; adsorption heat; porous structure.

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Оценка адсорбционных свойств пористого углеродного материала из «отработанного» кофе

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Аннотация: Статья посвящена изучению и оценке адсорбционных свойств нового высокопористого углеродного материала в широком интервале давлений при температурах выше критической. Показано, что активированный углеродный материал, полученный из «отработанного кофе» является эффективным адсорбентом для CH_4. Так, в данном исследовании карбонизированная кофейная гуща использовалась в качестве прекурсора для получения высокопористого углеродного материала (BУМ5), путем химической активации при 750 °C для эффективной адсорбции CH_4. Порометрия показывает, что полученный адсорбент является микромезопористым с узким

распределением пор по размерам, обладающий удельной площадью поверхности по БЭТ 3456 м^2/г и объемом пор 1,604 см^3/г. Изучена адсорбция CH_4 на полученном углеродном материале при температурах 298.15…323.15 K и давлении до 100 бар. BУМ5 демонстрирует высокую адсорбционную способность по CH_4 19 ммоль/г при 10 МПа и 298,15 K. Экспериментальные данные адсорбции CH_4 на BУМ5 проанализированы с использованием типовых моделей адсорбции Ленгмюра и Фрейндлиха в интервале температур 298,15…323,13 K. Результаты показывают, что адсорбция CH_4 на BУМ5 в рассматриваемом диапазоне температур и давлений соответствуют адсорбции Ленгмюра. Данный факт подтверждается полученными значениями коэффициентов корреляции равными 0,99 и средних относительных отклонений между экспериментальными результатами и результатами, полученными с помощью модели Ленгмюра, которые составляют менее 3 %. Рассчитаны значения изостерических теплот при различных абсолютных количествах адсорбции CH_4 на полученном BУМ5, которые находятся в диапазоне от ~10,0 до 17,0 кДж/моль, что указывает на то, что процесс представляет собой физическую адсорбцию, а сила связи между молекулой CH_4 и поверхностью адсорбента относится к силе Ван-дер-Ваальса. Данные изотерм адсорбции и термодинамические параметры, оцененные в настоящем исследовании, полезны для проектирования систем хранения газа на основе адсорбции.

Ключевые слова: адсорбция; углеродный адсорбент; метан; изотермы адсорбции; изостеры адсорбции; теплота адсорбции; пористая структура.

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1. Introduction

The greenhouse effect that causes global warming is the result of industrialization and the generation of gases such as methane (CH_4), carbon dioxide (CO_2), nitrogen oxide (N_2O) and others. Although the concentration of CH_4 in the atmosphere is lower than that of CO_2, the heating effect of CH_4 on a per molecule basis is 72 times greater than that of CO_2 [1]. Thus, the potential contribution of CH_4 emissions to global warming is 25 times higher than CO_2 [1]. At the concentration of CH_4 in the air of about 5–15 %, it is extremely explosive. When the concentration of CH_4 in the air reaches 30 %, it can cause headache, dizziness, fatigue, difficulty in breathing and rapid heartbeat, and even death by suffocation [2].

Adsorption is considered the most common approach to CH_4 removal because this method has several advantages including ease and simplicity of operation. Among various adsorbents, porous carbon materials are widely used for CH_4 removal due to their high specific surface area and total pore volume as well as a large number of surface functional groups [3].

In addition, the low sulphur and nitrogen content makes CH_4 a much cleaner burning fuel than commercial petrol [4]. Unfortunately, CH_4 has a low volumetric energy density, so its use is limited due to storage and transport problems. For this reason, its compression and storage is of great interest to the industrial and scientific community [5]. Current methods of CH_4 storage include its compression in high-pressure tanks (compressed natural gas – CNG) and/or storage in liquefied form (liquefied natural gas – LNG). CNG is produced at pressures of more than 200 bar, which imposes certain requirements on the design of storage tanks (in particular, wall thickness), which are then quite difficult to place inside passenger cars [6]. Compression to these pressures is also costly [7]. LNG is stored at temperatures below 111 K (mainly used for intercontinental transport). The need for lower temperatures also incurs costs, requires well-insulated expensive tanks, and presents significant safety issues due to pressure build-up from CH_4 boil-off if the vehicles are left idle for long periods of time [8]. These problems have prompted the investigation of various alternatives to increase CH_4 density. An alternative to CNG and LNG is the use of adsorbents to store CH_4 (adsorbed natural gas – ANG) with higher density at ambient temperature and moderate pressure [9]. In fact, CH_4 storage in solid materials offers advantages in terms of gravimetric and volumetric energy density, safety and energy efficiency [10]. For this reason, ANG technology is considered a promising solution for energy storage, especially in natural gas-fueled vehicles [11].

The U.S. Department of Energy (DOE) has set requirements for the gravimetric and/or volumetric adsorption capacity of adsorbents for methane uptake (0.5 g $CH_4 \cdot g^{-1}$ adsorbent and/or 263 cm^3 $CH_4 \cdot cm^{-3}$ adsorbent) [12, 13]. Various nanoporous materials have been studied for CH_4 storage, including metal-organic frameworks (MOFs) [14, 15], nanoporous carbon [16, 17], porous polymers [18], etc.

Biochar, carbon-rich materials obtained by thermal decomposition of agricultural and industrial biomass wastes under oxygen-free conditions, has been widely recognised as a viable alternative to activated carbon for CH_4 adsorption due to several advantages including cost effectiveness and easy access to raw materials. Currently, coffee waste has emerged as an attractive candidate for biochar production [19]. According to the literature [20–23] because of its physicochemical properties, coffee waste can be used as a raw material (precursor) to produce porous carbon adsorbent and investigate it as a CH_4 adsorbent.

In this regard, the aim of the work is to evaluate the adsorption properties of a porous carbon material from used coffee grounds and assess its potential as effective materials for ANG technology.

2. Materials and Methods

2.1. Activation technique

The synthesis of a highly porous carbon material (HPCM5) was carried out by alkaline activation of carbonised used coffee grounds with potassium hydroxide. The mass ratio of "spent" coffee carbonisate: KOH during activation was 1 : 5. Activation was carried out in a pilot reactor in argon flow at 750 °C for 1 hour. After activation, excess KOH was removed with 0.1 M hydrochloric acid solution and then the product was washed with distilled water until a neutral pH value was reached.

2.2. Determination of specific surface area and adsorption characteristics

The porous structure of the adsorbent HPCM5 was characterised by N_2 adsorption-desorption isotherms at liquid nitrogen temperature (77 K) using an automatic surface and porosity analyser Autosorb-iQ (Quantachrome, USA).

The adsorption characteristics of HPCM5 were evaluated in the temperature range of 298.15–323.13 K and up to a final pressure of 10 MPa. The material was degassed at 350 °C for 2 h before the adsorption experiment. Measurements of CH_4 sorption under high pressure were performed with an iSorbHP high pressure and temperature gas adsorption analyser manufactured by Anton Paar GmbH using high purity CH_4 (99.999 %).

2.3. Theoretical basis

Adsorption isotherms demonstrate the correlation of adsorption amount with pressure under isothermal conditions and are often treated using various sorption models [24]. The Langmuir (1) and Freundlich (2) models are the most widely used models.

Equation (1) is commonly used to describe adsorption data. This equation is based on gas adsorption by solids and is also known as monolayer adsorption theory [25]. With this model, it is assumed that adsorption occurs on a homogeneous solid surface.

$$a_L = \frac{Abp}{1+bp}, \qquad (1)$$

where a_L is the theoretical value of equilibrium gas adsorption according to the Langmuir model ($mmol \cdot g^{-1}$); p is the equilibrium pressure of the gas phase (MPa), A is the maximum adsorption capacity ($mmol \cdot g^{-1}$), b is the Langmuir adsorption constant, which depends on the properties of adsorbent, adsorbate and temperature. The larger the value of b, the higher the adsorption capacity of the material.

Equation (2) is an empirical formula that can be used to describe the theory of adsorption on a heterogeneous surface.

$$a_F = kp^{1/n}, \qquad (2)$$

where a_F is the theoretical value of equilibrium gas adsorption according to the Freundlich model. In the formula, n and k are two empirical constants that depend on temperature. The value of k can be viewed as the amount of adsorption per unit of pressure. Generally speaking, k decreases with a temperature increase; n is the heterogeneity coefficient representing the adsorption capacity of the material and its value is usually greater than 1. When its value is greater than 1, it shows that the material has good adsorption capacity for CH_4.

The validity of these models was assessed by the regression coefficient R^2, which ranges from 0 to 1, and the normalized standard deviation Δa (%) defined as:

$$\Delta a = 100\sqrt{\frac{\sum_{i=1}^{n}\left[\left(a_{\exp} - a_{\mathrm{mod}}\right)/a_{\exp}\right]^2}{N-1}}, \qquad (3)$$

where $a_{\exp}$ and a_{mod} are the gas adsorption values obtained from experiments and theoretical models, respectively, N is the number of data points of the adsorption isotherm.

The isosteric heat of adsorption is the enthalpy change that occurs during the adsorption process. It is calculated using the Clausius–Clapeyron equation [26]:

Table 1. Textural properties of the HPCM5 nanoporous carbon material

S_{BET}	S_{DFT}	V_{DFT}	$V_0 = V_{01} + V_{02}$	V_{03}	V_{01}	V_{02}	D_{01}	D_{02}	D_{03}
$m^2 \cdot g^{-1}$			$cm^3 \cdot g^{-1}$					nm	
3456	2469	1.604	0.739	0.865	0.401	0.338	0.92	1.61	3.09

where S_{BET} is the specific surface area by nitrogen calculated using the Brunauer–Emmett–Teller method; S_{DFT} is the specific surface area by nitrogen calculated using density functional theory; V_{01} is the specific pore volume of the first mode; V_{02} is the specific volume of pores of the second mode; V_0 is the specific volume of micropores; V_{03} is the specific volume of pores of mesopores; D_{01} is the average diameter (width) of pores of the first mode; D_{02} is the average diameter (width) of pores of the second mode; D_{03} is the average diameter (width) of pores of the third mode.

$$\left(\frac{d\ln p}{dT}\right)_n = -\frac{q_{st}}{RT^2}, \quad (4)$$

where R is the ideal gas constant, 8.314 $J\cdot(mol\cdot K)^{-1}$, T is the temperature (K), n is the specific amount adsorbed at pressure p and temperature T.
Hence:

$$q_{st} = -R\left(\frac{d\ln p}{d(1/T)}\right)_n. \quad (5)$$

3. Results and Discussion

3.1. Surface and porosity characteristics of HPCM

An important characteristic of each adsorbent is its specific surface area, which strongly influences its adsorption capacity. The values of specific surface area, micropore volume (less than 2 nm) and mesopore volume (2–50 nm) are good indicators of successful synthesis of HPCM prior to adsorption studies.

The pore parameters of the synthesised highly porous carbon material are summarised in Table 1.

The HPCM5 sample used in this study is a micromesoporous material ($V_0 = 0.739$ $cm^3\cdot g^{-1}$; $V_{03} = 0.865$ $cm^3\cdot g^{-1}$) with a narrow pore size distribution (less than 5 nm). The analysis showed that HPCM5 possesses a multimodal pore size distribution calculated using density functional theory (DFT); in particular, there are micropore peaks with maxima around 0.9 and 1.6 nm, as well as a mesopore peak with a maximum around 3.1 nm (Table 1). In addition, it should be noted that HPCM5 possesses a BET specific surface area of 3456 $m^2\cdot g^{-1}$ and a pore volume of 1.604 $cm^3\cdot g^{-1}$.

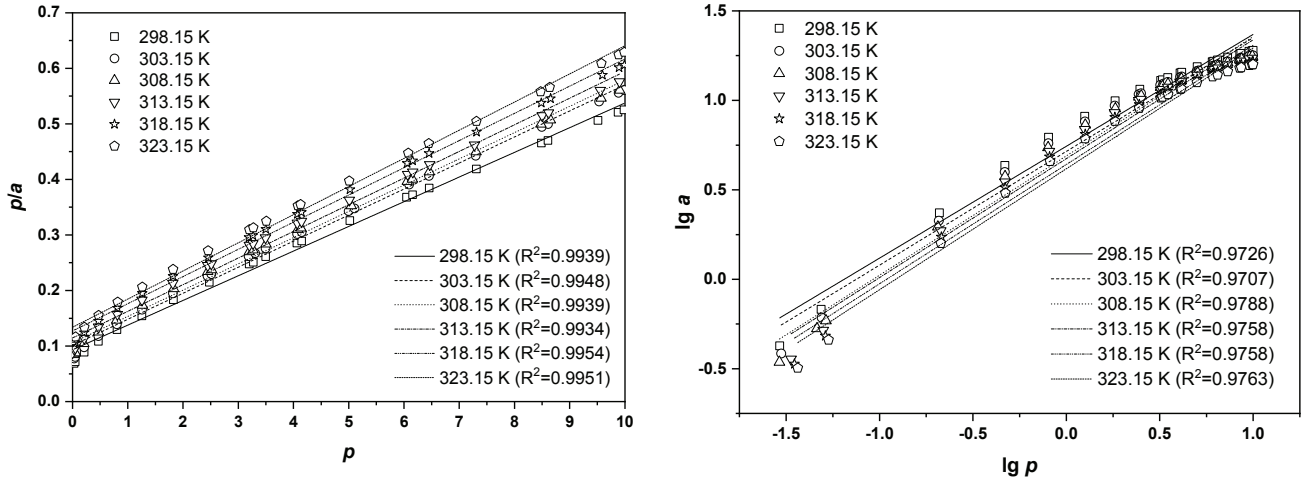
3.2. Adsorption characteristics of HPCM

Experimental data at six different temperatures (from 298.15 to 323.15K) were processed using the Langmuir and Freundlich models. Figure 1 shows the dependence of CH_4 sorption on the investigated HPCM5 sample in coordinates of the Langmuir and Freundlich models.

The CH_4 adsorption isotherms measured at temperatures 298.15, 303.15, 308.15, 313.15, 318.15, 323.15 K and pressure up to 10 MPa on the HPCM5 sample and the results of modelling of isothermal adsorption curves are presented in Fig. 2. The lines correspond to the Langmuir and Freundlich models and the dots represent the experimental data. The estimated Langmuir and Freundlich parameters for CH_4 on the HPCM5 sample at six different temperatures are given in Tables 2 and 3.

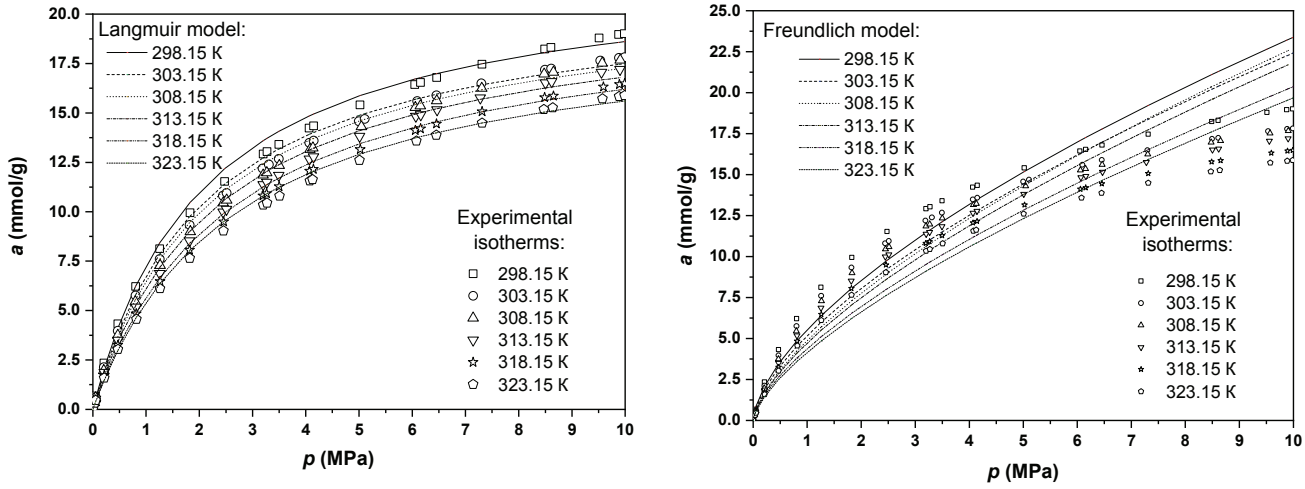
As can be seen from Fig. 2, the equilibrium adsorbed amounts of CH_4 increase with increasing pressure in the system, but the slope of the curves decreases at higher pressures, since in this case the adsorption centers approach saturation. In addition, Fig. 2 shows that temperature strongly affects the equilibrium adsorption capacity all else being equal. That is, as the adsorption temperature increases, the amount of adsorbed CH_4 decreases, which is due to the heat release during CH_4 adsorption. The maximum value of adsorption capacity of HCPM5 on CH_4 is 19 $mmol\cdot g^{-1}$ at 10 MPa and 298.15 K.

Figure 2*a* shows that the experimental data are in excellent agreement with the Langmuir model, which indicates that this isothermal model can be used to describe the investigated adsorption equilibrium. Another confirmation of the applicability of the Langmuir model to describe the obtained experimental data is the high value of the correlation coefficient R^2 (more than 0.99) and the



(*a*) (*b*)

Fig. 1. Dependence of CH_4 sorption on HPCM5 in the coordinates of the Langmuir (*a*) and Freundlich (*b*) models



(*a*) (*b*)

Fig. 2. CH_4 adsorption isotherms on HPCM5 at different temperatures, adapted according to the Langmuir (*a*) and Freundlich (*b*) models

Table 2. Adsorption isotherm coefficients for the Langmuir model

Temperature, K	a_{exp}	Langmuir constants				
		a_L mmol·g^{-1}	A	b	R^2	Δa, %
298.15	19.01	18.61	22.52	0.476	0.9939	8.97
303.15	17.81	17.49	21.23	0.468	0.9948	7.75
308.15	17.67	17.23	21.14	0.445	0.9939	8.14
313.15	17.20	16.79	20.83	0.419	0.9934	6.69
318.15	16.48	16.19	20.41	0.385	0.9954	6.56
323.15	15.88	15.60	19.72	0.379	0.9951	5.77

Table 3. Adsorption isotherm coefficients for the Freundlich model

Temperature, K	a_{exp}	Freundlich constants				
		a_F	k	n	R^2	Δa, %
	mmol·g^{-1}					
298.15	19.01	23.35	5.54	1.59	0.9726	17.89
303.15	17.81	22.41	5.19	1.57	0.9707	18.51
308.15	17.67	22.57	4.89	1.50	0.9788	17.61
313.15	17.20	21.70	4.73	1.50	0.9758	17.34
318.15	16.48	20.35	4.38	1.49	0.9758	17.97
323.15	15.88	19.66	4.14	1.48	0.9763	17.82

low value of the normalised standard deviation Δa (less than 10 %) (Table 2). Also, it should be noted that the values of theoretical values a_L of CH_4 adsorption on the HPCM5 sample obtained by the Langmuir model at different temperatures have a deviation from the experimentally obtained adsorption values a_{exp} of less than 3 %. However, as can be seen from Fig. 2*b*, the Freundlich model showed the worst agreement with the obtained experimental data of CH_4 adsorption on HPCM5 (R^2 =~0.97; Δa = ~18 %) (see Table 3).

Table 2 shows that the maximum adsorption value and Langmuir parameters decrease with increasing temperature. The increase in temperature leads to CH_4 molecules becoming more active and more difficult to retain on the surface of the HPCM5, which reduces the adsorption capacity. The value of the Langmuir parameter *b* shows the affinity of CH_4 molecules to the adsorbent surface, and when it decreases (Table 2), it indicates a gradual decrease in the affinity of CH_4 molecules to the HPCM5 surface with a temperature rise.

Experimental CH_4 adsorption isotherms were used to plot the isosteres, which represent the quantitative relationship between pressure and temperature at a constant adsorption value (Fig. 3).

Generally, the value of isosteric heat of adsorption (q_{st}) depends on the absolute value of adsorption [27]. Hence, the q_{st} values for the investigated sample were calculated for fifteen different absolute adsorption quantities equal to 0.1, 0.5, 1.0, 2.5, 4.0, 5.0, 6.0, 7.0, 7.5, 8.5, 9.5, 9.5, 10.5, 11.5, 12.5 and 13.5 mmol·g^{-1}. As can be seen from Fig. 3, the isosteres of CH_4 adsorption on HPCM5, plotted as the dependence of ln(p) on (1/T), are well approximated by a straight line.

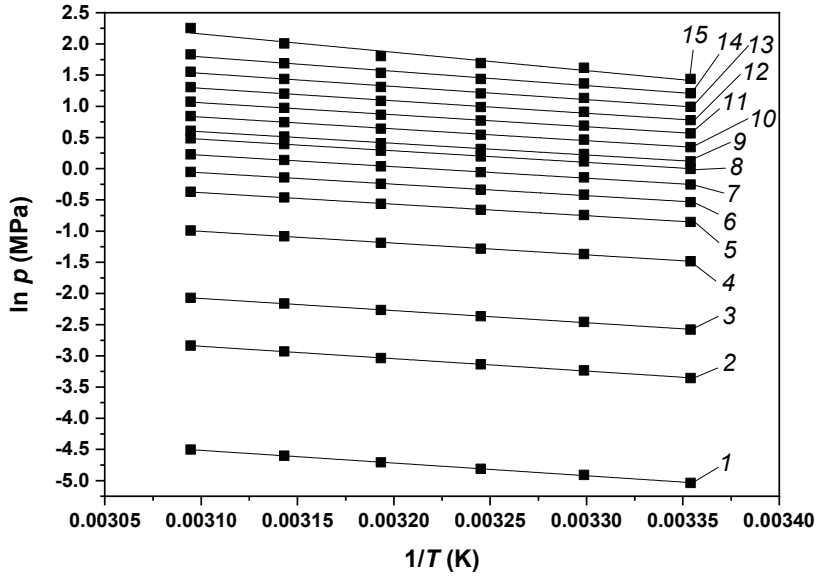


Fig. 3. The isosteres of CH_4 adsorption on HPCM5 during the adsorption process, mmol·g^{-1}: 0.1 (*1*), 0.5 (*2*), 1.0 (*3*), 2.5 (*4*), 4.0 (*5*), 5.0 (*6*), 6.0 (*7*), 7.0 (*8*), 7.5 (*9*), 8.5 (*10*), 9.5 (*11*), 10.5 (*12*), 11.5 (*13*), 12.5 (*14*), and 13.5 (*15*)

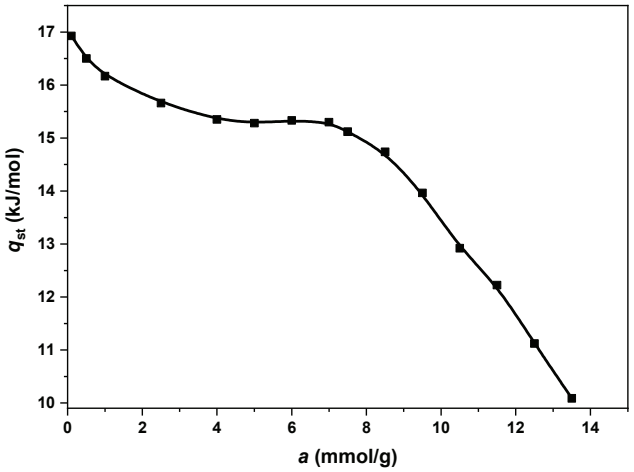


Fig. 4. Isosteric heat of adsorption of CH_4 on HCM5

The dependence of isosteric heat on the value of CH_4 adsorption on HPCM5 is shown in Fig. 4. As can be seen in the figure, q_{st} calculated by the Clausius–Clapeyron equation decreases with increasing adsorption amount. Also for the studied adsorption system, a high value of q_{st} is observed at the early stages of adsorption, when CH_4 molecules occupy most of the micropores, binding to high-energy adsorption centres.

Thus, at low adsorbate loadings, the absolute value of q_{st} depends on the density of adsorption centres, which are high-energy micropores with sizes comparable to those of adsorbate molecules. As the number of adsorbed molecules increases, the high-energy adsorption centres are completely filled and the adsorbate-adsorbate interactions contribute to the heat of adsorption. Thus, the dependence $q_{st} = f(a)$ reflects the change in the state of adsorbed molecules during adsorption – from binding to high-energy adsorption centres to the formation of molecular associates and their subsequent rearrangement close to saturation.

The q_{st} values at different absolute adsorption quantities for the HPCM5 sample range from ~17.0 to 10.0 kJ·mol^{-1}.

Since the heat of chemical adsorption usually ranges from 40 to 600 kJ·mol^{-1}, this indicates that the predominant adsorption process of CH_4 on the investigated sample is physical adsorption [28], and the bonding force between the CH_4 molecule and the adsorbent surface refers to the van der Waals force [29].

From the practical side of the issue of calculating the ANG system capacity, the absolute content adsorption value is not indicative, since it takes into account only CH_4 in the adsorbed state. However, in order to understand the total capacity, the gas phase in the space between the granules of porous materials should also be considered. The volumetric active specific capacity of the system and the adsorption active gravimetric capacity of the porous materials are important for the performance of the ANG system.

The CH_4 adsorption capacity of the HPCM has been measured at 298 K and pressures up to 10 MPa. Levels of gravimetric and volumetric adsorption of methane on HPCM5 are shown in Fig. 5.

Thus, HPCM5 showed a gravimetric adsorption of 0.51 g·g^{-1} (106 m^3 (STP) · m^{-3}) at the corresponding pressure of 10 MPa and temperature of 298 K. However, due to the low packing density, the obtained experimental data on CH_4 volumetric absorption are somewhat lower than required for the application of the considered materials as adsorbents for ANG technology.

It is possible to solve this problem, namely to increase the volumetric capacity of carbon structures for CH_4 storage, by increasing the packing density, i.e. by reducing the space between the granules. However, in this case it is also necessary to optimize the packing parameters, investigating the influence of key conditions of the process implementation (compaction pressure, type of binder, degree of adsorbent dispersion, as well as the size and shape of adsorbent particles) on the properties of the obtained materials. Also, it is necessary to control the nature of pore structure change during mechanical compaction.

In order to evaluate the potential of HPCM5 as adsorbents for ANG technology, it is important to compare the gravimetric CH_4 adsorption capacity with other commonly investigated adsorbents. Figure 6 presents a comparison of the gravimetric CH_4 uptake

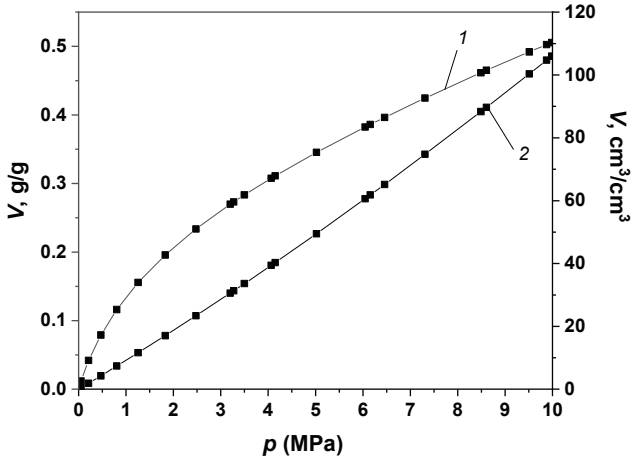


Fig. 5. Plotting of gravimetric (*1*) and volumetric (*2*) absorptions of methane *V* from pressure *p*up to 10 MPa on HPCM5 adsorbent at 298 K

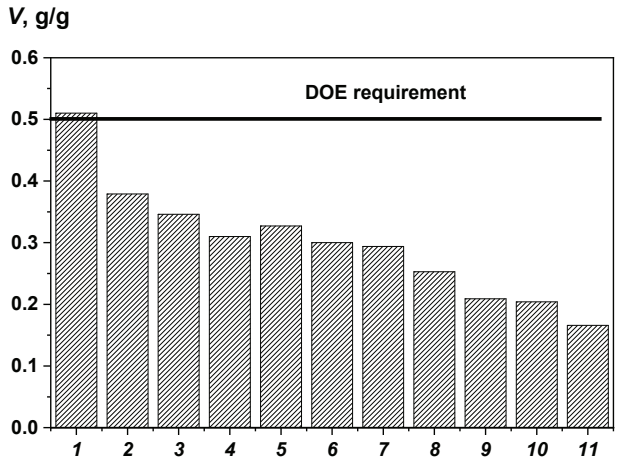


Fig. 6. Comparison of CH_4 operating capacities for selected methane adsorbents: *1* – this study; *2* – BUT-22; *3* – PPN-4; *4* – AX-21; *5* – ZJU-36; *6* – Maxsorb III; *7* – MOF-5; *8* – NOTT-102; *9* – UTSA-76; *10* – Co(bdp); *11* – HKUST-1

for some selected methane adsorbents: BUT-22 (296 K, 8 MPa), PPN-4 (298 K, 5.5 MPa), AX-21 (248 K, 10 MPa), ZJU-36 (240 K, 6.5 MPa), Maxsorb III (298 K, 8 MPa), MOF-5 (248 K, 10 MPa) NOTT-102 (273 K, 6.5 MPa) UTSA-76 (273 K, 6.5 MPa) Co(bdp) (273 K, 6.5 MPa), HKUST-1 (298 K, 10 MPa) [30–41].

The results show that the gravimetric capacity of HPCM5 exceeds the gravimetric working capacity of the examined CH_4 adsorbents. Since such properties as surface area, pore volume and packing density of carbon materials can be adjusted during synthesis, the materials obtained from coffee waste have a high potential for their use as adsorbents for ANG technology. In addition, adsorbents derived from coffee waste can be cheaper to produce than metal-organic frameworks (MOFs), which currently show high adsorption capacities towards CH_4.

4. Conclusion

Activated carbon material obtained from coffee waste is an effective CH_4 adsorbent. The sample of highly porous carbon material (HPCM5) used in this study is a micromesoporous adsorbent having a BET specific surface area of 3456 $m^2 \cdot g^{-1}$ and a pore volume of 1.604 $cm^3 \cdot g^{-1}$.

The adsorption of CH_4 on HPCM5 has been investigated and the experimental data have been analysed using the Langmuir and Freundlich adsorption models in the temperature range 298.15–323.13 K and pressure up to 10 MPa. The results show that the adsorption of CH_4 on HPCM5 over the range of temperatures and pressures considered in this study is consistent with the Langmuir adsorption, and this is confirmed by the high values of the correlation coefficient (greater than 0.99) and low values of the normalised standard deviation (less than 10 %). In addition, it is found that the average relative deviations between the experimental results and the data obtained using the Langmuir model are less than 3 %. The maximum value of CH_4 adsorption capacity of HPCM5 is 19 $mmol \cdot g^{-1}$ at 298.15 K and 10 MPa.

Adsorption isosteres are plotted. The dependence of isosteric heat of adsorption of CH_4 on HPCM5 was calculated. It is shown that the values of isosteric heat at different absolute amounts of adsorption for the sample of HPCM5 decrease from ~17.0 to 10.0 $kJ \cdot mol^{-1}$.

The adsorption capacity of HPCM5 was studied in terms of gravimetric and volumetric capacity for CH_4 at 293 K and pressure up to 10 MPa. It was found that the level of gravimetric adsorption of CH_4 corresponds to the requirements formed by the U.S. Department of Energy, and the HPCM5's volumetric specific capacity for CH_4 is slightly lower than DOE requirements, due to low packing density.

It is worth noting that the performance characteristics of carbon materials derived from used coffee grounds are generally comparable to adsorbents of other classes. However, the experimental data indicate that the resultant materials have a high potential and that further studies are needed to optimise the physicochemical and functional properties of the adsorbents.

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6. Conflict of interests

The authors declare no conflict of interests.

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