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Adsorbed natural gas storage and transportation vessels

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Abstract—Adsorbed natural gas (ANG) storage and transportation technology recently became competitive to compressed natural gas (CNG) method due to a high energy density capability achievements. New adsorbents such as monolithic carbons and recently compressed active carbon fibers used in noncylindrical vessels have made possible to store the same capacity of gas as CNG tanks, but at much lower pressure. New types of gas tanks thermal control systems with internal source of energy input, based on heat pipe heat exchangers, make it possible to use different sources of energy (exhausted gases, wasted engine cooling liquids, solar and other types of energy) to stimulate gas desorption at constant rate of gas delivery and constant pressure (temperature) and avoid the drop of temperature in the storage tank due to the enthalpy of desorption. © 2000 Éditions scientifiques et médicales Elsevier SAS

storage / adsorption / transport / new adsorbents / heat pipe / monolithic and fiber carbon

Nomenclature

a	adsorption capacity	$kg{\cdot}kg^{-1}$
c	gas density	$kg{\cdot}m^{3}$
C	solid sorbent specific heat capacity	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
C_g	gas specific heat capacity	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
C_a	adsorbed methane specific heat capacity	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
D_{sd}	surface diffusion	$m^2{\cdot}s^{-1}$
D_{s0}	pre-exponent constant	$m^2{\cdot}s^{-1}$
E	energy of activation	$J{\cdot}kg^{-1}$
G	gas output from the vessel	$kg{\cdot}s^{-1}$, $g{\cdot}s^{-1}$
g	gas output from one cylinder, $= G/n$	$kg{\cdot}s^{-1}$
g	gas output from the elementary cell, used for computer modeling	$kg{\cdot}s^{-1}$
K_{s0}	pre-exponent constant in the equation of kinetic of sorption	s^{-1}
M	mass	kg
N	number of cells in cylinder	
n	number of cylinders	
P	pressure	MPa, Pa
Q	heat flow	W
q_{st}	latent (isosteric) heat of adsorption	$J{\cdot}kg^{-1}$
r, z	coordinates	
r_0, r_1	internal and external radii of the sorbent bed inside the cylinder	m
R	external radii of vessel envelope	m
R_g	gas constant	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
R_p	mean radii of the particle	m
R_0	internal radii of heat pipe envelope	m
$2S$	distance between fins	m, mm
T	temperature	°C, K
V	volume	m^3
v_a	specific volume of adsorbed medium	
W_0	maximum micropores volume	
v	vector component of the gas velocity	$m{\cdot}s^{-1}$

Greek symbols

α	heat transfer coefficient	$W{\cdot}m^{-2}{\cdot}K^{-1}$
ε	porosity	
2δ	fin thickness	m, mm
λ	sorbent bed effective thermal conductivity	$W{\cdot}m^{-1}{\cdot}K^{-1}$
ρ	solid sorbent density	$kg{\cdot}m^{-3}$
ρ_v	volumetric sorbent bed density	$m^3{\cdot}m^{-3}$
τ	time	s

Subscripts

a	adsorbent
c	carbon
cr	critical conditions
e	final value
eq	conditions of equilibrium
env	surrounding
f	fin
g	gas
hp	heat pipe
p	particle
s	sorbent

sd	surface diffusion
st	stage transition
s0	surface
ν	meso and macropores
void	void
μ	micropores
0	initial value

0. INTRODUCTION

To make adsorbed natural gas systems competitive to compressed natural gas (CNG), gasoline or diesel fuel, the cost of its storage and refueling systems must be reduced drastically. Application of a physical adsorption phenomenon in the solid media is one way to solve this problem.

ANG technology based on natural gas adsorption in porous materials at relatively low pressures 3.5–4 MPa is a challenge to the liquid fuel application. Using lower vessel pressures offers two main benefits: it allows a good design flexibility in tank configuration and placement and reduces the cost to compress natural gas to high pressures.

ANG systems have also some benefits such as low pressure in noncylindrical containers, low capital and operating cost of compression and refueling equipment, reduced global warming potential due to the low energy consumption for compression. Environmental protection initiatives of different environmental agencies have led to intensification of research efforts on ozone and global warming safe gas-fired heat pump technology. Actually the ANG tanks are mostly developed to replace CNG vessels for vehicles, but in the near future some other applications for adsorbent technologies are transparent, such as gas-fired solid sorption heat pumps, because they are absolutely benign for the environment, ANG storage systems used as gas holders for peak shaving operations, gas-fired drying chambers, ANG big tanks transportation, liquefied petroleum gas (LPG) — propane replace systems, emergency fuel, etc.

The one of the first experiments with ANG storage systems were performed in Russia [1, 2], in the Institute of Rural Mineral Resources under the Professor Dubinin leadership. Two different types of active carbons were used for methane storage at the pressure interval 0.1–100 MPa and room temperatures. Important rise in the methane adsorption capacity was found with the pressure increasing up to 5–6 MPa. An application of the pulverized active carbon for ANG tanks with 5–10 times increasing of methane storage capacity ($P = 3.5$ MPa) was discussed in [3]. Actually, Ford Motor Company suggests a low pressure ANG storage vessel for vehicles [4–6], which has the same gas capacity at 2 MPa as a CNG tank at 15 MPa. AGLARG Co., USA, has developed a noncylindrical tank for the low pressure ANG storage in vehicles [7, 8]. The most important ANG storage systems are filled with active carbons made from cellulose sources (coconut shells, peach pits) and from noncellulose polyvinylidenechloride (PVDC). PVDC carbons are also used for composite carbons fabrication. New types of PVDC carbons were developed in the former USSR [9] and used for methane adsorption with good capacity for storage.

A two-dimensional model was developed [10] to describe the hydrodynamic heat transfer and adsorption phenomena associated with the adsorptive storage of methane in cylindrical vessels. The problem of nonisothermal behavior of the ANG vessels during discharge was analyzed in [11]. Modern ANG storage vessels need to be competitive with CNG, LPG and liquid fuel tanks. To gain the goal of this problem it is necessary to develop a high-performance microporous adsorbent material and an advanced system of the tank thermal control. For the Republic of Belarus the natural gas is a prime fuel, which is imported from Russia at 16.6 billion m^3 per year. Natural gas needs to be stored and transported through over the country and replaces LPG-systems. Gas-fired solid sorption heat pumps and air-conditioning systems are the most convenient mode of local heating/cooling technologies. ANG storage vessels nowadays have an increasing role as an alternative to CNG storage systems both for micro heat machines application (heat pumps and refrigerators, air-conditioning devices) and for macro storage and transportation system applications (ANG tanks for peak shaving operations, ANG tanks for naval and rail-road transportation, emergency fuel resources). The most important is a possibility for ANG storage vessel to be used as a vehicle source of energy. ANG vessels are environmentally safer than gasoline vehicles producing 99 % less CO, 30 % less NO_x, 96 % less HCs. The car equipped with an ANG storage system has such advances to compare with a liquid fuel car:

- the time of a car application is extended up to 1.5,
- the time of the oil service is increased up to 1.5–2,
- the period of the ignition system service is extended up to 40 %,
- the noise of the working engine is reduced down to 7–9 dB,
- the $(CO)_n$ exhaust concentration is reduced down to 4–6 times,

- the $(NO)_n$ exhaust concentration is reduced down to 1.3–1.9 times.

Actually at least two types of ANG storage systems related with vehicles (buses) are the subject of current interest and need to be considered:

- ANG vessels for the vehicle,
- ANG tanks as a stationary gas storage system situated at the end bus stops, used to refuel buses.

In this paper two types of an active carbon system for methane storage are considered and the radial gas distribution with internal heat generation/dissipation is suggested.

1. THEORETICAL MODEL

This simple model (*figure 1*) of cylindrical ANG vessel with internal finned heater disposed on its axis is based on such assumptions:

(1) uniform pressure is assumed within a porous structure during the gas charge/discharge inside the ANG vessel;

(2) the demand rate of gas consumption is constant with constant pressure drop with the time;

(3) instantaneous phase equilibrium is assumed between adsorbed and gaseous methane; the local temperature of adsorbed bed and free gas volume is the same due to a high heat transfer intensity between solid and gas;

(4) the gas inside macropores is considered as ideal;

(5) the energy conversion during the gas expansion, or compression is negligibly small;

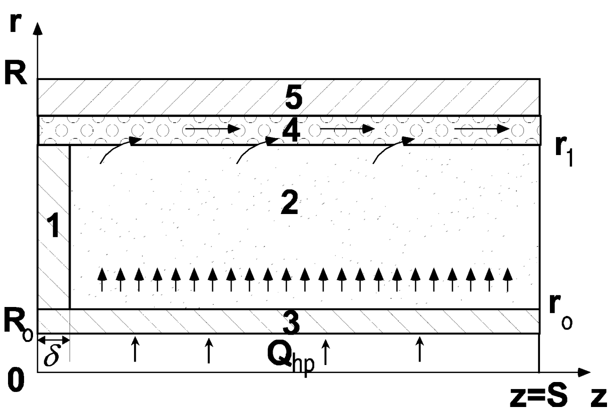

Figure 1. Schematic of the cylindrical sorbent bed element with a finned tube for heating. 1: fin, 2: sorbent bed, 3: heater (heat pipe), 4: gas channel, 5: vessel envelope.

(6) there is only radial gas flow through the bed;

(7) the resistance of mass diffusion is small.

The dynamic model has five components: (1) the equation of energy; (2) the isosteric heat of desorption; (3) the equation of continuity; (4) the equation of the kinetic of sorption; (5) the Dubinin and Radushkevich relationship between the gas volume adsorbed in micropore, a_{eq}, and adsorption potential.

- The energy equation:

$$r(\varepsilon c C_g + \rho C + \rho a C_a)\frac{\partial T}{\partial \tau} + r c v C_g \frac{\partial T}{\partial r} = \frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(r\lambda \frac{\partial T}{\partial z}\right) + r q_{st}\rho \frac{\partial a}{\partial \tau} \quad (1)$$

where the isosteric heat of desorption is

$$q_{st} = R_g T\left[\frac{\partial \ln P}{\partial \ln T}\right]_{a=\mathrm{const}} \quad (2)$$

- The equation of continuity:

$$r\frac{\partial}{\partial \tau}(\varepsilon c + \rho a) + \frac{\partial}{\partial z}(r c v) = 0 \quad (3)$$

- The equation of kinetic of sorption:

$$\frac{\mathrm{d}a}{\mathrm{d}\tau} = K_{s0}\exp\left(-\frac{E}{R_g T}\right)(a_{eq} - a) \quad (4)$$

where $K_{s0} = 15D_{s0}/R_p^2$, D_{s0} is a constant necessary to determine the coefficient of a surface diffusion, $D_{sd} = D_{s0}\exp[E/(R_g T)]$.

- Dubinin and Radushkevich equation of the state of gas

$$a_{eq} = \frac{W_0}{v_a}\exp\left(-D\left[R_g T \ln\left(\left(\frac{T}{T_{cr}}\right)^2 \frac{P_{cr}}{P}\right)\right]^2\right) \quad (5)$$

The solution was found for the fixed gas flow from the ANG vessel

$$2\pi\frac{\mathrm{d}}{\mathrm{d}\tau}\int_{\delta}^{S}\int_{r_0}^{r_1}(\varepsilon c + \rho a) r\,\mathrm{d}r\,\mathrm{d}z = -\frac{g}{N} \quad (6)$$

with boundary conditions:

$$P\big|_{\tau=0} = P_0, \qquad T(r,z)\big|_{\tau=0} = T_0(r,z) = T_{env} \quad (7)$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0, \qquad \left.\frac{\partial T}{\partial z}\right|_{z=S} = 0$$
$$-\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R} = \alpha_{env}(T - T_{env}) \quad (8)$$

$$-\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R_0} = \frac{Q_{hp}}{2\pi R_0 S N} \quad \text{or} \quad T\big|_{r=R_0} = T_{hp} \quad (9)$$

where Q_{hp} is the heat flow used to heat one cylinder of the vessel, T_{hp} is the ANG wall temperature.

To solve the set of equations (1)–(5) with boundary conditions (7)–(9) the method of finite elements was chosen on fixed grid. The number of triangular elements in the considered area was from 200 up to 300. The algorithm of iterations was used to solve the set of equations with mutual justification.

It is necessary to note that the pressure gradient in the ANG vessel is small (< 700 Pa) and there are no reasons to solve the equation of momentum.

The suggested simple model gives us a possibility to obtain the field of temperature and gas concentrations during discharge procedure of the ANG vessel.

2. EXPERIMENTAL SET-UP

The experimental set-up is shown in *figure 2*. The analysis of isotherms of methane at the temperature interval $-0\,°C$–$+60\,°C$ and pressure interval 0.1–5 MPa was realized by the gravimetric control of the sample ("Busofit") during adsorption/desorption cycle. The cylindrical experimental rig of 47 mm inner diameter and 540 mm length was used to simulate full-scale conditions of the experiment. This experimental rig was made from stainless steel and served as a simulator of the real vessel in the ratio 1 : 50. The electric heater (later it was a heat pipe heater) was placed on the axis of the sample. Three thermocouples were attached to the sample with distance of 4 mm through the sorbent bed (12.5 mm thick) in radial direction. A pressure sensor was used for pressure measurements in the experimental chamber.

Free gas volume inside the experimental rig was determined using He technology, *figure 2*. Helium was supplied from the He bottle 13 to the calibrated control vessel 9 through the regulated valve 14. After this procedure the valve 18 was closed and the valve 8 was opened to joint the control vessel 9 with the experimen-

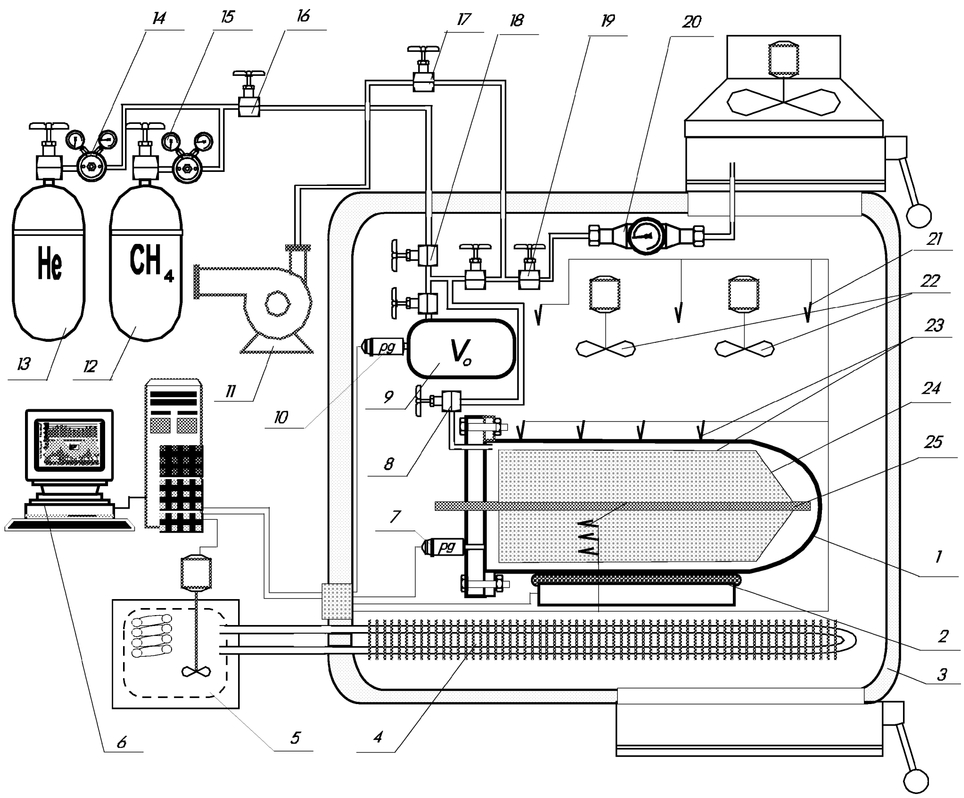

Figure 2. Experimental set-up. 1: ANG cylinder, 2: electronic balance, 3: insulated chamber, 4: heat exchanger, 5: thermostat, 6: computer with software, 7, 10: pressure sensors, 8, 16–19: valves, 9: calibrated volume, 11: vacuum pump, 12: methane vessel, 13: helium vessel, 14, 15: reducer, 20: flow meter, 21, 23: thermocouples, 22: fans, 23: thermocouple, 24: sorbent bed, 25: heat exchanger.

tal rig 1. Pressure sensor 10 was used to fix the pressure drop. The free gas volume inside the experimental rig was obtained using the Clapeyron–Mendeleev equation.

Before the experiments for obtaining methane isotherms the active carbon fiber sample was fully desorbed in vacuum chamber with its heating up to 350 °C during 5 hours. All the time the pressure inside the chamber was controlled. After sorbent bed was fully desorbed and cooled up to a room temperature, a calibrated mass of methane was supplied to the chamber from the methane tank 12 through the regulated valve 15 and valves 8, 16, 18. The temperature field inside the guard chamber 3 was controlled by heat exchanger 4 and thermostat 5. The fan 22 inside the experimental chamber 3 stimulated the air circulation, its temperature being controlled by the thermocouple 21. The mass evolution of adsorbed methane was checked with an electronic balance 2, the valve 8 being closed.

A special software (Delphi) was used to analyze methane isotherm behavior during experiments based on temperature (thermocouples 21, 23) and pressure (sensors 7, 10) data.

The type of adsorbent implemented strongly influence of dynamic adsorption capacity of methane and is an important step in the design of a performing sorption process.

Different modifications of an activated carbon fiber “Busofit” (“Busofit-4-055”, “Busofit-055”, “Busofit AYTM-055”) were investigated as an adsorbent for methane storage. “Busofit” is produced from pyrolized cellulose activated by water vapor.

Now it is clear that ANG storage vessels filled with “Busofit” have some benefits such as high methane storage capacity near 130 $m^3 \cdot m^{-3}$. The material could be made as a loose fibers bed, or as monolithic blocks with binder to have a good thermal conductivity along the filaments. “Busofit” can be used as a compact sandwich with flat heat pipes applied as thermal control systems. It can be considered as a typical microporous adsorbent with pore diameter near 1–2 nm (*figures 3–5*) and at the same time as a material with good gas permeability. The micropore distribution is performed mostly on the carbon filament surface. To minimize a void space and increase the adsorbent capacity the active carbon fibers need to be compressed together with a binder. Nowadays a program was undertaken to examine the parameters of an active carbon fiber to optimize both the mass uptake of methane and the carbon density. “Busofit” is an universal adsorbent which is efficient to adsorb different gases (H_2, N_2, O_2, CH_4, NH_3, etc.). “Busofit” has such advantages as:

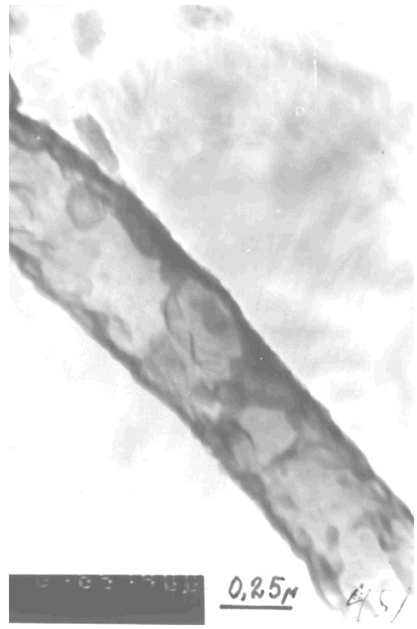

Figure 3. Active carbon fiber “Busofit AYTM-055” element. Image multiplied by 50 000 times.

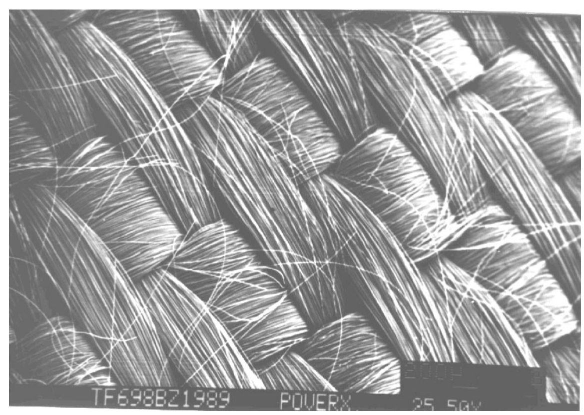

Figure 4. Active carbon fiber “Busofit AYTM-055” element. Image multiplied by 50 times.

- high rate of adsorption and desorption,
- uniform surface pore distribution (0.6–1.6 nm),
- small number of macropores (100–200 nm), with its specific surface 0.5–2 $m^2 \cdot g^{-1}$,
- small number of mesopores with 50 $m^2 \cdot g^{-1}$ specific surface.

The total volume V, associated with an active carbon adsorbent may be split up into its components:

$$V = V_c + V_\mu + V_\nu + V_{void} \tag{10}$$

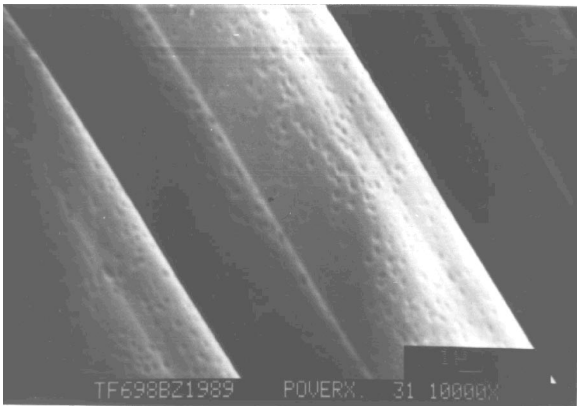

Figure 5. Active carbon fiber “Busofit AYTM-055” element. Image multiplied by 10 000 times.

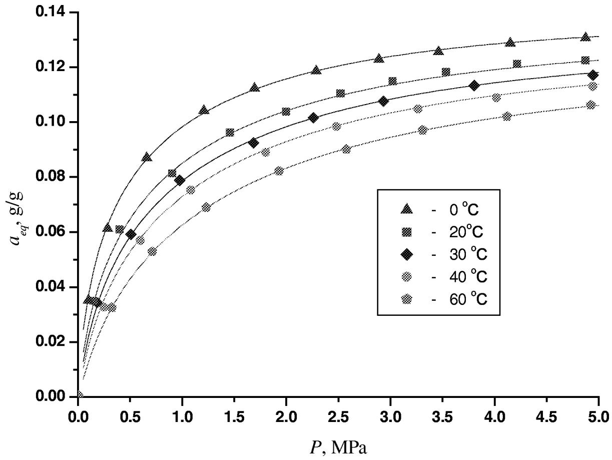

Figure 6. Active carbon fiber “Busofit AYTM-055”. Methane sorption isotherms: experimental data, points; calculated data (Dubinin–Radushkevich equation [1]), lines.

where V_c is the volume of the carbon atoms of which the adsorbent is composed; V_μ micropores volume; V_ν meso- and macropores volume; V_{void} the space inside the vessel free from adsorbent bed. This latter V_{void} can be eliminated by making the solid block of adsorbent (compressed with binder).

The advanced ANG needs to have micropores volume near 50 %, solid carbon near 40 % and meso/macropores volume near 10 %. When larger vessels with fast gas sorption/desorption rate need to be used, the gas transport problems are important. The packing density greater than 0.6 g·ml^{-1}, which is optimal for small vessels, is difficult to achieve in big tanks.

Methane isotherms evolution during the cycle of adsorption/desorption of “Busofit” is shown in *figure 6*. Full and dynamic adsorption capacity for three different types of “Busofit” is shown in *table I*. Based on these data we can conclude that “Busofit” is competitive to best active carbons with methane adsorption capacity 113–135 kg·kg^{-1} at 273 K. It is possible for “Busofit” to have its full desorption at room temperature (only 15 % of methane is remaining in the sorbent bed).

The experimental set-up was used to compare the data of numerical modelling and the experimental data for “Busofit” and other sorbent beds. The ANG vessel (7 cylinders) with total volume of 43 dm^3 was tested. The calculations were made for one cylinder with volume 6.14 dm^3. This ANG vessel was filled with an active carbon fiber “Busofit-AYTM”, which has mostly micropores. To observe the structure of “Busofit” filaments we need to use a high resolution scanning electron microscope (*figures 3–5*).

The initial temperature of the vessel was equal to the room temperature $T_{\text{env}} = 285$ K, vessel was not

TABLE I
Methane adsorption capacity for three different types of an active carbon fiber “Busofit”.

Sample	S, m^2·g^{-1}	$a_{\max}$, g·g^{-1}	a_{cyc}, g·g^{-1}
“Busofit TM-4-055”	1 400	0.113	0.098
“Busofit AYTM-055”	1 560	0.119	0.105
“Busofit TM-055”	1 510	0.115	0.101

heated ($Q_{\text{hp}} = 0$ W), initial pressure inside the vessel was 3.5 MPa, final pressure inside the vessel was 0.3 MPa. The heat transfer coefficient ($\alpha_{\text{env}} = 0$ W·m^{-2}·K^{-1}) on the outer vessel surface was assumed as zero.

The empirical coefficients in the equations (1)–(5) were assumed as

$$W_0 = 0.501\ \text{cm}^3\cdot\text{g}^{-1}$$

$$D = \frac{1.93\cdot 10^{-6}}{R_g^2}\ \text{K}^{-2}$$

$$\frac{E}{R_g} = 890\ \text{K}^{-1}$$

$$K_{s0} = 7.35\cdot 10^{-2}\ \text{s}^{-1}$$

During the experiments insulated ANG vessel (adiabatic conditions) was discharging with constant gas rate 25 dm^3·min^{-1}. The temperature fall was checked inside the sorbent bed due to the heat sink (heat of desorption) action from 285 down to 260 K. The experimental data of the pressure, adsorption capacity and temperature evolution during the ANG vessel discharge were compared with the data of numerical analysis (*figure 7*). Following the methane constant rate of release (curve 2) after 1.5 h

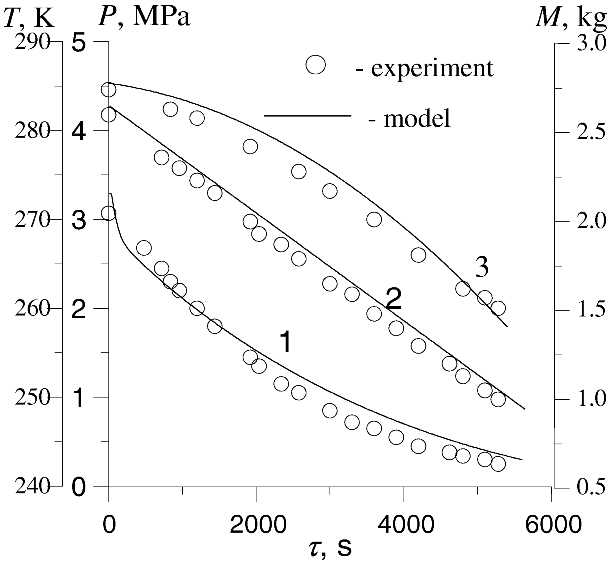

Figure 7. Pressure P (1), mass of methane M (2), and temperature T (3) evolution inside one of the cylinders of the ANG vessel during its discharge. $T_{env} = 285$ K.

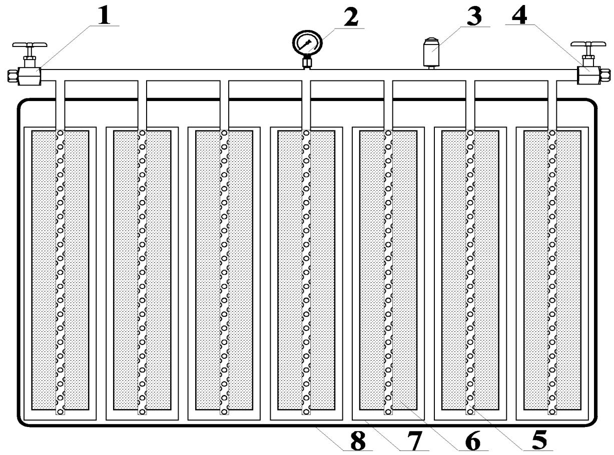

Figure 8. 7 cylinders ANG vessel with radial gas and energy transfer. 1: valve for gas charge, 2: pressure gauge, 3: valve, 4: joint valve for the car engine gas supply, 5: perforated tube for radial gas distribution, 6: sorbent bed, 7, 8: ANG vessel.

of gas consumption the mass of gas was reduced from 2.5 down to 1.0 kg.

There is sufficient agreement for "Busofit" between experimental data and numerical analysis data during desorption procedure for pressure evolution (curve 1), adsorption capacity decrease (curve 2), and temperature evolution (curve 3). It is important to note that "Busofit" can be considered as a "fast" sorbent due to its ability to adsorb methane molecules mostly in its surface. "Busofit" fibers maximum adsorption and dymanic adsorption capacity are close to each other (*table I*). For example, for "Busofit AYTM-055" maximum adsorption capacity is 0.119 kg·kg^{-1}. It means that 1 kg of solid carbon adsorbs 119 g of methane at room temperature. Dynamic adsorption capacity of this sorbent is 0.105 kg·kg^{-1}. It means that 1 kg of solid carbon during the cycles adsorption/desorption adsorbs and desorbs 105 g of methane. "Busofit" specific surface opened for adsorption is equal $S = 1\,560$ m^2·g^{-1}. As it is shown in *figure 5* "Busofit" has uniform regular pore distribution on the surface of filaments. Carbon fibers can be oriented on the heat flow direction, for such a case its effective thermal conductivity ought to be high. All the data (*table I*) are obtained at room temperature (20 °C). The same procedure of methane charging/discharging realised in adiabatic conditions reduced "Busofit" dynamic adsorption capacity by 38 %.

The main drawback of "Busofit" by now is its cost. Conventional active carbons made from peach pits or coconut shell have at least two times lower cost. Therefore, some experiments were realized with an active carbon pellets "207C". These experiments were also performed using 7 cylinders ANG vessel made from stainless steel, the cylinders were filled with carbon pellets. Each cylinder has a gas distribution perforated pipe, disposed along its axis and ensured radial gas flow motion across the sorbent bed (*figure 8*). The experimental set-up has a valve 1 for gas supply, pressure gauge 2 for pressure evolution control during the experiment; valves 3, 4 as safety opening and for the car engine gas supply. Each cylinder has its sorbent bed 6 and tube for gas distribution 5. The results of the experiments are summarised in *table II*. We need to note that methane isotherms for the active

TABLE II
ANG vessel parameters.

Parameters	Value
ANG vessel length, mm	1 565
ANG vessel width, mm	758
ANG vessel height, mm	140
Number of cylinders	7
ANG vessel volume, l	43
ANG vessel mass, kg	31.9
Length of cylinder, mm	1 475
Outer diameter of cylinder, mm	76
Inner diameter of cylinder, mm	73
Mass of sorbent bed (active carbon "207C"), kg	20.55
Volumetric gas storage density of sorbent bed, nm^3·m^{-3}	80–100
Total gas volume in the ANG vessel, nm^3	3.9
Temperature of ANG vessel, °C	−40–+40
Pressure of the ANG vessel, MPa	3–4

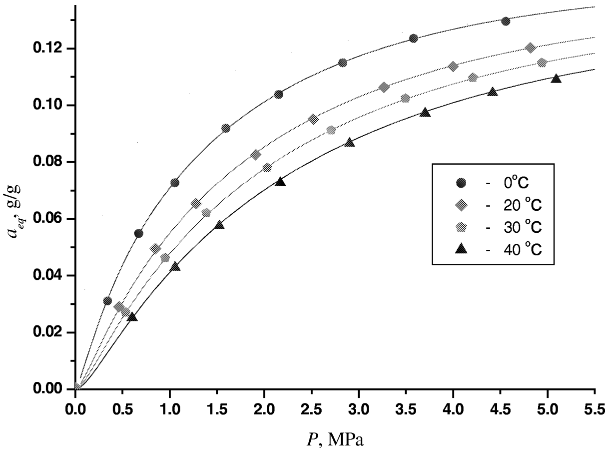

Figure 9. Active carbon "207C". Methane sorption isotherms: experimental data, points; calculated data (Dubinin-Radushkevich equation [1]), lines.

carbon pellets "207C" are similar to "Busofit" isotherms (*figure 9*). The most essential difference is in its rate of adsorption. "Busofit" rate of adsorption is several times more and the cycle adsorption/desorption for "Busofit" could be shorter. "Busofit" as activated carbon fiber material has pores of small diameter and the approach of Dubinin [1, 2] is well adapted and allows to link quite simply the physical properties of the activated carbon fiber to the capacity of methane adsorption of the material. Today we can count several hundreds of activated carbons. The type of sorbent bed strongly influences the sorption capacity. The choice of an adapted activated carbon is an important step in the ANG vessel design. "Busofit" is one of advanced active carbons for modern ANG tanks.

The next important step is related with ANG vessel thermal control. In our experiments heat pipe heat exchangers were used to enhance heat transfer between the sorbent bed and the surroundings, or between the sorbent bed and heater. An advanced 14 cylinder ANG vessel 1, shown in *figure 10*, for methane storage and transportation is suggested, which is made from an aluminium profile, produced by die extrusion process with six finned heat pipes 2 inside. Fins 5 are used to heat the sorbent bed 3 during the time of discharge. This heat pipe heat exchanger is used to cool sorbent bed during vessel charging with methane. Gas channels 4 ensure efficient gas output during the service time. Heat pipes 2 have a good thermal contact with a combustion gas exhaust tube, or to be supplied with an electric heater. Monolithic "Busofit" disks are inserted into the ANG cylinders and have a good thermal contact with finned heat pipes. Such disks have a high effective thermal conductivity in radial direction to decrease the temperature drop during the gas re-

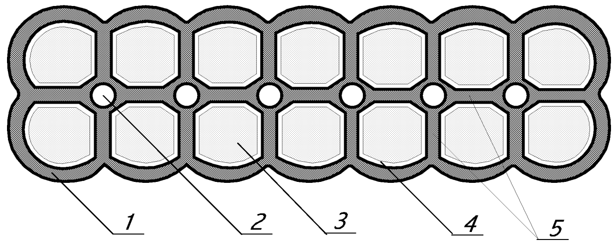

Figure 10. 14 cylinder ANG vessel for methane storage, cross section. 1: vessel envelope, 2: heating elements (heat pipes), 3: sorbent bed, 4: gas channels, 5: metal fins to heat/cool a sorbent bed.

lease from a sorbent bed. The role of ANG vessel thermal control based on heat pipe application will be analyzed in the near future.

3. ANG VESSELS FOR HEAT PUMPS AND REFRIGERATORS

Another alternative to the ANG vessels application is gas-fired heat pumps. They offer many benefits to consumers, utilities, and the regional and global environment. The autonomous source of energy as an ANG vessel with its convenient noncylindric shape is a unique system for gas-fired solid sorption machines, especially for vehicles. There is a direct similarity between the ANG vessel and solid sorption adsorber of such machine. Both need to be heated during desorption cycle and cooled during adsorption cycle. The difference is in the time of this cycle. For ANG vessels this time is long (some hours) and for the solid sorption machines this cycle is short (some minutes). The ANG vessel during its discharge could be considered as a heat sink for the solid sorption machine (something like its condenser surface) to increase its COP. Good thermal contact between the ANG vessel and solid sorption machine is essential and can be ensured by heat pipe heat exchangers. An example is the ANG vessel as a source of gas for an infrared gas burner. This gas burner is used as a heating system for a gas-fired solid sorption heat pump (*figure 11*).

4. CONCLUSIONS

1. A new type of microporous material "Busofit", active carbon fiber disks, product of pyrolized cellulose was suggested, tested and analyzed as an advanced adsorbent, capable of delivering near 150 volumes of methane per volume of the ANG vessel at pressure 3.5 MPa.

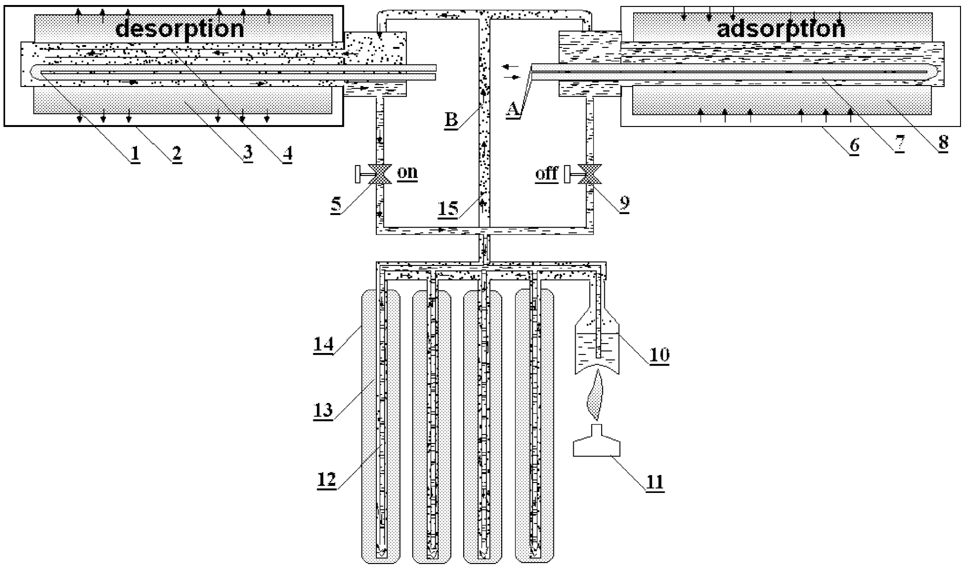

Figure 11. Alternative solar/gas heat pump, heating/cooling system. 1, 7: water heat exchangers, 2, 6: adsorbers, 3, 8: sorption beds, 4: vapour channel inside the condenser of the two-phase heat transfer device, 5, 9: valves, 10, 13: water boilers, 11: gas heater, 12: liquid channel, 14: vacuum tube collector, 15: vapour pipe; A: city water, B: vapour.

2. A simple theoretical model of cylindrical ANG vessel with radial gas distribution during desorption and internal finned heater for thermal control was suggested.

3. Methane sorption isotherms for “Busofit” in the temperature range 0–60 °C were experimentally obtained and verified with the data following Dubinin equation with good accuracy.

4. Experimental data for the pressure drop, adsorption capacity and temperature drop in the “Busofit” sorbent bed during its gas discharge were compared with theoretical data.

5. A new type of a multicell ANG vessel for methane storage and transportation was suggested with a heat pipe thermal control inside.

6. Some future possibilities to apply ANG vessels with gas-fired solid sorption machines are discussed.

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