BIOLOGICAL ENGINEERING

ADSORBED METHANE GAS STORAGE SYSTEM BY USING GRANULAR ACTIVATED CARBON

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ABSTRACT

Energy recovery from wastes represents an important trend to reduce the amount of an electricity energy that is produced from fossil fuels. Adsorbed methane gas (AMG) storage technology count a recent alternative and will compete with strongly the compressed methane gas technology by virtue of achievement capability for a high energy density. The innovative technology utilizes the attendant property of an activated carbon adsorbent and its general tendency for methane gas storage near the from liquid phase in a high energy density. The current study presents the method implementation for adsorbed methane gas system aiming to store gas under different adsorption pressures and temperatures with a high density as well to improve the heat exchange process for adsorption and desorption cycles. This is achieved by design and installation a heat exchanger been beside gas tank as type of thermal control systems, allowing to store a larger amount of adsorbed gas by reducing the temperature of the gas before the storage process. Performance evaluation of the developed system was based on the following indicators: storage pressure, adsorption efficiency, gas flow rate and energy production as well the energy balance (net energy output) of the gas storage system. The developed system is capable of storage 170 Volume/Volume with an adsorption efficiency of 94.40% which is equivalent to 18.89 kWh of net energy output at pressure of 3 MPa and adsorption temperature 283 °K.

1. INTRODUCTION

Energy crisis and escalating costs of fossil fuel resources have prompted the investigation of new approaches to meet future energy requirements. Decreasing conventional energy resources coupled with climate change concerns also have procured global attention toward the development of alternative, renewable, carbon-neutral and eco-friendly fuels to satisfy the growing energy needs.

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Optimum and sustainable alternative for the conventional fuels and their environmental impacts is biogas energy, which can provide a strategy to diversify energy sources to decrease supply risks as well help to enhance domestic economies (**Mohan and Pandey 2019**).

In spite of the features offered by the compressed methane gas in comparison to raw biogas, there is a significant disadvantage can be summarized in low-energy density (heat of combustion per volume unit) as well remains in gas phase under normal conditions of pressure and temperature which constitutes a challenge for some applications. Therefore, the storage of methane gas, whether in density or quantity, plays significant role for its use in several applications. As an alternative technique for gases storage, the adsorbed natural gas (ANG) system, which can storages gas at a relatively low pressure (3–4 MPa), The gas store capacity is even higher in this system than that of compressed natural gas system which storages natural gas at pressure 20 MPa (**Park et al., 2018**). Adsorption phenomenon is defined as the obtain of one or more of the gas constituents in the zone of the gas-solid interface. It is a phenomenon in which interaction surface plays a significant role. The occurrence of adsorption phenomenon in gas-solid interactions is main focus of attention to achieve a significant increment of the gas density (**Solar et al., 2010**). Compressed methane technique may lead to the risk of highly compressed gas within the storage cylinder which requires taking some necessary precautions as thick-walled cylinders and a safety valves complicated. Therefore, the storage of methane gas, whether in density or quantity, plays significant role for its use in several applications. Among the different adsorbents, activated carbon has been considered the most proper adsorbents because of their micro-porosity, a high surface area and renewal capacity (**Srinivas et al., 2012**). The activated carbon is used to storage of natural gas at a low pressure of ranging from 2 to 4 MPa at the room temperature, which represents a potential alternative for the applications at large scale. This technology is not well developed and is still at research and experimentation level. The studies on storage methods by the ANG process is carried out using the adsorbent material. It has found that the density of the compressed gas at 3.4 MPa can be increased in a value higher than 4 times by the use of adsorbent material, reaching a gas storage capacity of 180 Volume/Volume

(**Marsh and Rodriguez 2006**). Compressed natural gas technology is no longer viable alternatives to petroleum fuel due to the high cost of high-pressure storage vessels requiring a large amount of space with a low energy density. Adsorbed natural gas technology has been considered a potential pathway for solving the problems that compressed natural gas presents, because it allows for conformal vessel designs that can be squeezed into less size. ANG is stored at lower pressures (3.4 - 4.5 MPa) relative to compressed natural gas (24.8 MPa), which enhances safety and the potential for minimized operating costs (**Dubois, 2017**). Adsorbed natural gas container is based on the gas adsorption in the micro-pores of an adsorbent material bed, which offers a density approaching the liquid phase. Adsorbed container provides overall storage capacity of 164 V/V with pressure ranging from 35.46 to 50.66 bar at room temperature. These features make adsorbed containers as an interesting means to ensure gas retention under a low pressure and temperature. Adsorption process is exothermic this behavior reduces gas storage capacity because the saturation of adsorbed gas decrease with an increase temperature. Therefore, cooling process can improve the efficiency of adsorbed natural gas container (**Amigo et al., 2018**). An experimental study was carried out charge-discharge cycles for hydrocarbon gas mixture of propane and butane into a volumetric device loaded with different activated carbons during cyclic operation. It was noticed that the highest storage capacities were (62, 65 and 67 V/V) for the chemical activated carbon, steam-nitrogen activated carbon and Commercial activated carbon under low pressure of 0.4 MPa and at 303°K temperature (**Yahia and Ouederni 2012**). One of the key challenges in adsorbed natural gas technique is the management of thermal effects. The adsorption heat significantly impacts adsorbed gas storage capacity even for the adsorbents with a high surface area. Which requires gas cooling before is injected into the vessel filled with adsorbent (**El-Sharkawy et al., 2016) and (Li et al., 2018**).

Therefore, the current study was interested in manufacture and the performance evaluation of an adsorbed methane gas storage system using granular activated carbon. Objectives of this study included manufacture and evaluation performance of an adsorbed methane gas (AMG) system in various operating conditions as well as to optimize some operating

parameters (adsorption pressures and temperatures) affecting performance of the methane gas storage system. Tubular heat exchanger also was designed to cool the gas under different operating conditions. In addition to design the electrical operating circuit and controller circuit for an adsorbed methane gas system.

2. MATERIALS AND METHOD

The experiments were conducted at Biogas Laboratory, Agricultural Engineering Department, Faculty of Agriculture, Zagazig University to construct and the performance evaluation of an adsorbed methane gas storage system using activated carbon.

Granular activated carbon

Carbon used in the experiments was activated by using a pyrolysis process in a shape granular to suit operating requirements as shown Table 1. Granular activated carbon can be reused and reactivated many times.

Table 1: Main physical characteristics of activated carbon.

Surface area, $m^2.g^{-1}$	800
Particle size, mm	10
Bulk density, $kg^{-1}.m^3$	450
Fixed carbon, %	87.8
Ash content, %	1.8
Moisture content, %	6.0
Thermal conductivity, $W.m^{-1}.K^{-1}$	0.54
Specific heat, $kJ.kg^{-1}.K^{-1}$	0.65

Physical and thermal properties

Properties of fuel gases are subject to variations and their estimation is considered offer a utility tool for several calculations and applications. Some physical and thermal properties were determined for biomethane in comparison with natural gas as given in Table 2. Values are given for gas phase at standard conditions, STP (273^oK and 101.325 kPa).

Adsorbed methane gas (AMG) storage system

The adsorption system consisted of storage cylinder, upgrading unit, gas compressor, pressure switch, pressure relief valve, pressure gauge, heat exchanger, electronic control unit, gas outlet valve, activated carbon bed as shown in Fig. 1. The entire system was assembled and tested to be operated at different adsorption pressure and temperature levels. Temperature of the adsorption system was controlled by an electronic control unit. A vacuum tool

was connected to the adsorption cylinder to allow by regeneration of the used adsorbent as well as to help empty any gas held in the adsorbent material prior to the adsorption experiments.

Table 2: Physical and thermal properties for methane and natural gas.

Property	Biomethane	Natural Gas
Physical state	Adsorbed Gas	Gas
Molecular weight, g.mol^{-1}	16.04	18.20
Density, kg.m^{-3}	0.717	0.777
Relative density	0.555	0.601
Lower Heating Value, MJ.m^{-3}	35.85	36.60
Specific Heat Ratio	1.30	1.26
Gas Constant, kJ/kg K	0.52	0.49
Dynamic Viscosity, Pa.s	1.03×10^{-5}	1.06×10^{-5}
Kinematic Viscosity, m^2.s^{-1}	14.17×10^{-6}	15.16×10^{-6}

All dimensions in, mm

No.	Part Name	No.	Part Name
1	Adsorption Cylinder	9	Heat Exchanger
2	Biogas Discharge Port	10	Steering Arm
3	Upgrading Unit	11	Electronic Control Unit
4	Electric operation circuit	12	Gas Outlet Valve
5	Gas Compressor	13	Methane Outlet Port
6	Pressure Switch	14	Main Frame
7	Pressure Relief Valve	15	Activated Carbon Bed
8	Pressure Gauge	16	Cylinder Drain

Fig. 1: Schematic diagram of an adsorbed methane gas storage system.

METHOD:

The existing study was aimed to manufacture and evaluation performance of an adsorbed methane gas (AMG) as well as to optimize some operating parameters for achieving both of a high storage capacity and the net energy output as well as decrease adsorption heat to minimize temperature variation in the storage cylinder during the adsorption process through the cooling process by heat exchanger.

Storage cylinder

Gas storage cylinder was filled by porous material able to store methane gas at high energy density and a low pressure through adsorption process. This phenomenon reasons methane gas molecules to accumulate on the micro-pores surface of activated carbon in a high density near the from liquid phase. Methane gas can either flow through or around particles inside the packed cylinder in view of the small pores size of microporous activated carbon thus, most of the gas will easily flow around particles.

Heat exchanger model

Adsorbed gas storage process is an exothermic process, so must be rejected the heat evolved during the storage process. In this study, tubular heat exchanger was designed to suit the adsorbed methane gas system. A heat exchanger will be used as a necessary requirement that will cool the gas stream to control the heat of adsorption to prevent temperature change in the adsorbent bed and to facilitate the transfer of heat through forced convection thus achieving efficient storage system under different operating conditions.

Design of Heat Exchanger

The design criteria for heat exchanger includes estimation of the heat transfer area required for specified heat transfer rate and the pressure drop across the heat exchanger. Heat exchanger calculations require a value for the heat transfer rate, Q_{HE}, which can be determined from the specified flow rate of the methane gas, its specific heat capacity and the temperature change by using the following equation (**Cengel and Boles 2015**).

$$Q_{HE} = m\, C_p\, \Delta T$$

Where: m is mass flow rate of the gas, (kg.s^{-1}); Cp is specific heat capacity, (J/kg°K); ΔT is the change in temperature, °K.

$$Q_{HE} = 1.70 \times 10^{-3} \times 2.232 \times 25 = 0.095 \text{ kJ.s}^{-1}$$

The following formula can be used as a design equation to calculate the designed heat transfer surface area by knowing overall heat transfer coefficient, U, ($W.m^{-2}.°K^{-1}$):

$$A_D = \frac{Q_{HE}}{U \times \Delta T} = \frac{0.095 \times 10^3}{120 \times 25} = 31.70 \times 10^{-3} \ m^2 = 317 \ cm^2$$

Over-design represents extra surface area provided beyond that surface area designed to compensate for pollute, therefore typical value of 10% is acceptable in this case. According to the previous equation the required heat transfer surface area, A_{req} is 400 cm^2 in this heat exchanger. After having determined the required heat transfer surface area, the pressure losses or frictional pressure dropped can be calculated. The pressure dropped for gas stream through the heat exchanger passages is calculated as follows:

$$\Delta P = \frac{F \ \rho_m \ L \ v^2}{2D}$$

Where F is Darcy-Weisbach friction factor, ρ_m is density of methane gas, $kg.m^{-3}$, L is pipe length, m; v is average flow velocity of gas, $m.s^{-1}$ and D is pipe diameter, m and μ is the dynamic viscosity of methane, Pa.s.

$$R_e = \frac{D \ v \ \rho}{\mu} = \frac{6.35 \times 10^{-3} \times 74.59 \times 0.717}{1.03 \times 10^{-5}} = 32971$$

$$F = (100.Re)^{-\frac{1}{4}} = 0.023$$

$$\Delta P = \frac{0.023 \times 0.717 \times 5 \times 74.59^2}{2 \times 6.35 \times 10^{-3}} = 36.12 kpa$$

Description of the experimental system

The experimental system consists of production and upgrading biogas as well as adsorbed methane gas storage system using activated carbon. The experimental system has three different stages as follows:

Stage 1 and 2: Production and upgrading process

The first stage included production of biogas through anaerobic bio-digester with volume of 700 l that could produce 1.5 m^3 raw biogas per day under mesophilic condition. Through upgrading technique in the second phase carbon dioxide is separated from the raw biogas, some of the other undesired compounds are separated like hydrogen sulfide and water vapor as well. The raw biogas was filtered before the upgrading process to prevent mechanical wear and corrosion of the system equipment. This will result in an increased

energy density view of the concentration of methane gas is increased. Raw biogas is passed through iron oxide to remove hydrogen sulfide done by dry oxidation process where H_2S reacts with iron oxide to form iron sulfide. Immediately thereafter, Carbon dioxide is removed using scrubber column where carbon dioxide is dissolved in the water to increase the methane concentration in the gas phase it. The water leaving the scrubber column is transferred to a recycle tank where it runs across an opposite flow of air into which Co_2 will be released. As for the water vapor it is removed by a membrane filter of silica gel. This process produces of 95% pure methane gas. It is therefore significant constructing an improved upgrading system in terms of low power and material consumption achieving high methane content in the upgraded biogas.

Stage 3: Adsorption system

After purification process, the purified gas is bottled with storage pressure from 1 to 4 MPa by using an adsorbed methane gas storage system. The current study presents the method implementation for adsorbed methane gas system aiming to store gas at a low pressure and high density as well to improve the heat exchange process for adsorption and desorption cycles. When the internal pressure decreases in the storage cylinder molecules of methane gas are released from the adsorbent material surface into the gaseous state. This is achieved by the placement of granular activated carbon bed in order to maximize of the mass of gas adsorbed by end of the filling cycle and the minimization of mass after the discharge cycle. This system substitutes a high-pressure compressed methane gas to a low-pressure adsorbed methane gas (AMG) in a method that can be used on the application-scale.

Typical absorption cycle

Typical absorption cycle

The methane gas enters the compressor at room temperature and low pressure in the gaseous state through process in which it is increased both pressure and temperature. Next, isobaric heat rejection process, the pressurized and superheated gas from compressor outlet is transmitted to the heat exchanger for de-heats the gas before it is then entering into the storage cylinder. Followed by an isenthalpic expansion process from a high pressure to a low pressure by using expansion valve. For continues gas to fill the storage

cylinder an increase in temperature and at pressure constant until the adsorbent material is fully saturated.

The performance of the adsorbed methane gas system was experimentally measured under the following parameters; four different pressures (1, 2, 3, and 4MPa) and adsorption temperatures (283, 288, 293 and 298°K). Biogas production and purification process were also carried out under constant operating conditions throughout the experiment.

Electrical operation and controller circuit

The electrical circuit and controller circuit is designed for an adsorbed gas storage system as shown in Fig. 2. This system is provided with rewireable fuse, which uses so as to protect components and wires from an electrical overload or short circuit. The gas compressor, capacitor-start single phase motor is used in adsorption process. Current relay is provided to connect auxiliary winding on the start and disconnect it while the motor increases the speed. An overload protector is used to conserve the motor from damage against of overcurrent flow. Heating thermostat switch is supplied to control the temperature inside an adsorbed gas storage system. Temperature inside the storage cylinder can be adjusted via temperature control screw. Controller circuit was designed for controlling the fan speed of heat exchanger and therefore controlling the temperature of the stored gas. The fan motor speed can be controlled by changing the setting of potentiometer, P1. The potentiometer setting determines the phase of the trigger pulse that fires the diac and triac. This leads to a voltage increase in R2-P1 and C2-C3 causing the triac, T1 to be triggered earlier and accordingly, the speed increases. The controller circuit incorporates a self-stabilizing technique that maintains the motor speed when it is loaded. As the AC supply voltage increases at the beginning of the operation cycle, capacitors, C2 and C3 are charged through the combination of the resistor, R1 and the potentiometer, P1 and the voltage across its terminals increases. When the charging-voltage reaches the break-over voltage of the diac, it breaks down and the capacitor discharges through the diac. The discharge produces an abrupt pulse of the current, leading the triac into conduction. Can be controlled the charging rate of the capacitor using P1. The resistor, R1 limits the gate current to safe value when P1 is at its minimum. Once the triac has been into conduction, it is maintained in "ON" status by the load current flowing through it, while the voltage across the

resistor–capacitor combination is limited by the "ON" voltage of the triac and is maintained until end of the operating cycle.
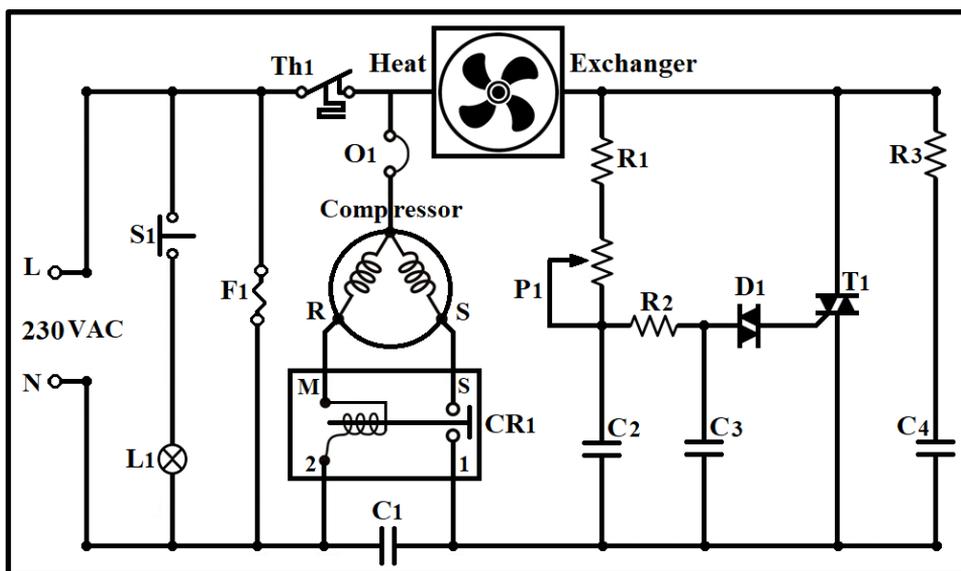
Symbol	Name	Specifications
S1	On-off Switch	250VAC-20A
L1	Indicator Lamp	230VAC-20mA
F1	Rewireable Fuse	5A White
Th1	Heating Thermostat	1° to 90°C-120/240 VAC
O1	Overload Protector	2hP 220V-50/60HZ
CR1	Current Relay	230VAC-20A
C1	Starting Capacitor	20μF-450VAC-50/60HZ
R1, R2 and R3	Resistance	30kΩ, 15KΩ and 100Ω
P1	Potentiometer	500kΩ
C2 and C3	Capacitors	100μF/400V
D1	DIAC	KR206
T1	TRIAC	KT207/400V-5A
C4	Capacitor	0.22μF/400V

Fig. 2: Schematic diagram of electrical operation and controller circuit.

Measurements and determinations:

There are important considerations for evaluating the performance of (AMG) storage system can be summarized in the following indicators:

1. Storage capacity (SC)

The gas storage capacity is referred as the volume/volume that the system can storage during adsorption cycle as shown in the following equation (**Yahia and Ouederni, 2012**).

$$SC = \frac{V_r}{V_c}$$

Where: V_r is volume of methane gas retained in the adsorbent material at the adsorption cycle end. and V_c is volume of storage cylinder.

2. Adsorption Efficiency (η_a)

The adsorption efficiency is given by the relation between the storage capacity and the theoretical capacity (**Cengel and Boles 2015**).

$$\eta_a = \frac{SC}{TC}$$

Where: SC is the storage capacity and TC is the theoretical capacity.

3. Compressibility Factor (CF)

Compressibility factor value is usually obtained by calculation from the state equation which taking specific compound constants as follows (**Cengel and Boles 2015**).

$$CF = \frac{P_d}{\rho_{act} \ R \ T_a}$$

Where: P_d is the discharge pressure, ρ_{act} is actual density of methane gas as shown in result table 3 and R is gas constant, and the T_a is an adsorption temperature $=283°K$.

4. Gas flow rate (Qv)

Volumetric flow rate can be calculated by using the following equation (**Cengel and Boles 2015**).

$$Q_V = \frac{V_g}{t}$$

Where: V_g is volume of obtained methane sample and t is the time consumed in the treatment operation.

5. Energy production (EP)

Energy production represents one of the important indicators which clarifies the possibility conversion of methane gas into power directly. The following equation could be used to calculate the amount of energy generated from methane gas.

$$EP = Q_V \times \rho_m \times \%_{CH4} \times LHV \times \frac{1}{CF} \times \eta_c$$

Where: Q_V is Gas flow rate and ρ_m is methane density $= 0.717$ kg.m^{-3}.

$\%_{CH4}$ is percentage of methane obtained after upgrading process $= 95\%$.

LHV is lower heating value $= 35.85$ MJ.m^{-3} and CF is conversion factor $= 3.6$.

η_c is Conversion efficiency to electricity $= 35\%$.

6. Energy consumption (EC)

The specific energy consumption can be calculated using the following equation (**Surroop and Mohee, 2012**).

$$EC = [P_C + P_{HE}] \times SF$$
$$EC = [(P_m \times \eta_m) + P_{HE}] \times SF$$

Where: P_c is power required for operating gas compressor.

P_{HE} is power required for heat exchange $= 100$ W.

SF is service factor assumed to be 1.25 to operate continuously.

P_m is power of motor compressor $= 1.10$ kW (1.5 hp).

η_m is mechanical efficiency $= 85\%$.

7. Wobbe Index (I_w)

Wobbe index is an important criterion of interchangeability of fuel gases and their relative ability to deliver energy. Which can be calculated by the lower heating value and specific gas density as follows (**Corre and Loubar, 2010**).

$$I_w = \frac{LHV}{\sqrt{\rho_R}} \; and \; \rho_R = \frac{\rho_m}{\rho_a}$$

Where: I_w is the lower wobbe index, ρ_R is the relative density, ρ_m is density of methane and assumed that ρa is density of air $= 1.292$ kg.m^{-3}.

3. RESULTS AND DISCUSSION

This technology utilizes the attendant property of an activated carbon adsorbent and its general tendency for methane gas storage near the from liquid phase in a high energy density. whereby under low pressurized conditions the widely carbon porosity enhances for greatly the volume storage of a purified methane gas. The obtained results will be discussed under the following items:

Storage capacity

Storage capacity can be seen as an expansion factor describing the expected change in bringing the methane gas from adsorption conditions to standard operating conditions. The results show that a gas storage capacity was significantly increased by increasing storage pressure up to 3 MPa, any further

increase in storage pressure up to 4 MPa storage capacity will decrease as shown in Fig. 3.
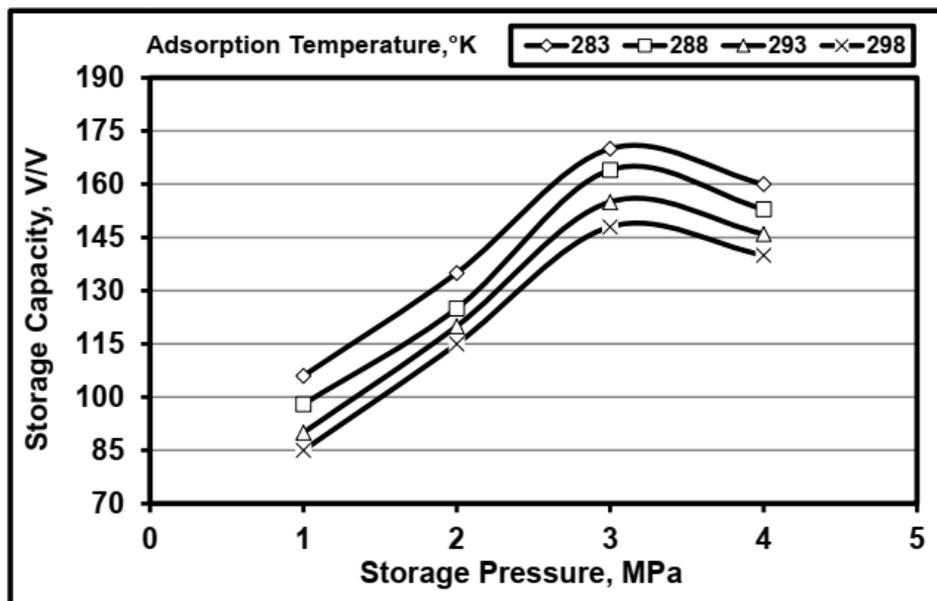
Fig. 3: Storage capacity as a function of pressure and temperature.

It was noticed that the storage capacity values were (148, 155, 164 and 170 V/V) measured at adsorption temperatures of 298, 293, 288 and 283 °K respectively and under storage pressure of 3 MPa. While the values were (85, 90, 98 and 106 V/V) under storage pressure of 1 MPa and the same pervious temperatures respectively. The experimental results showed that temperature have an obvious impact on the reduction of adsorption capacity during storage process. This different temperature impact on adsorption process can be attributed to the differences in composition activated carbon, mineral substances and pore structures. The gas storage capacity increased by increasing storage pressure up on 3 MPa because of the increase of gas adsorbed volume inside storage cylinder. While storage capacity decreased by increasing storage pressure up on 4 MPa this can be attributed to reduce pore size of carbon media during the experimental conditions.

Adsorption Efficiency

Representative values of adsorption efficiency versus storage pressure at adsorption temperatures is given in Fig. 4. Results show that increasing pressure from 1 to 3 MPa measured at adsorption temperatures of 298, 293,

288 and 283 °K, increased adsorption efficiency from 47.20 to 82.20, from 50.00 to 86.10, from 54.40 to 91.10 and from 58.90 to 94.40%, respectively.
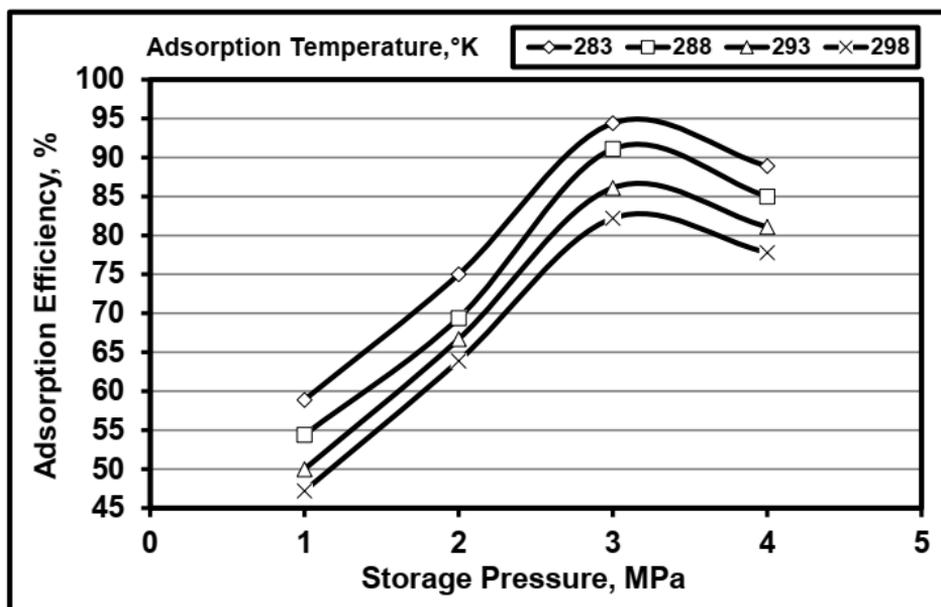
Fig. 4: Effect of pressure and temperature on adsorption efficiency.

The further increase in storage pressure from 3 to 4 MPa, measured at the same previous adsorption temperatures decreased adsorption efficiency from 82.20 to 77.80, from 86.10 to 81.10, from 91.10 to 85.00 and from 94.40 to 88.90 %, respectively. Higher values of storage pressure more than the optimum value tend to decrease adsorption efficiency because the high-pressure rates destroy the basic structure of activated carbon is greater than that low rates. Lower values of storage pressure less than the optimum value tend to decrease efficiency because of decrease actual storage capacity of methane gas under low pressure rates.

Gas flow rate

As can be given from Fig. 5, storage pressure has significant influence on volumetric flow rate. It was evident that the gas flow rate values were (7.40, 7.75, 8.20 and 8.50 $m^3.h^{-1}$) measured at adsorption temperatures of 298, 293, 288 and 283 °K respectively and under storage pressure of 3 MPa. While the values were (4.25, 4.50, 4.90 and 5.30 $m^3.h^{-1}$) under the same pervious temperatures respectively and at storage pressure of 1 MPa. Discharge pressure is one of the sensitive parameters which control gas flow rate.
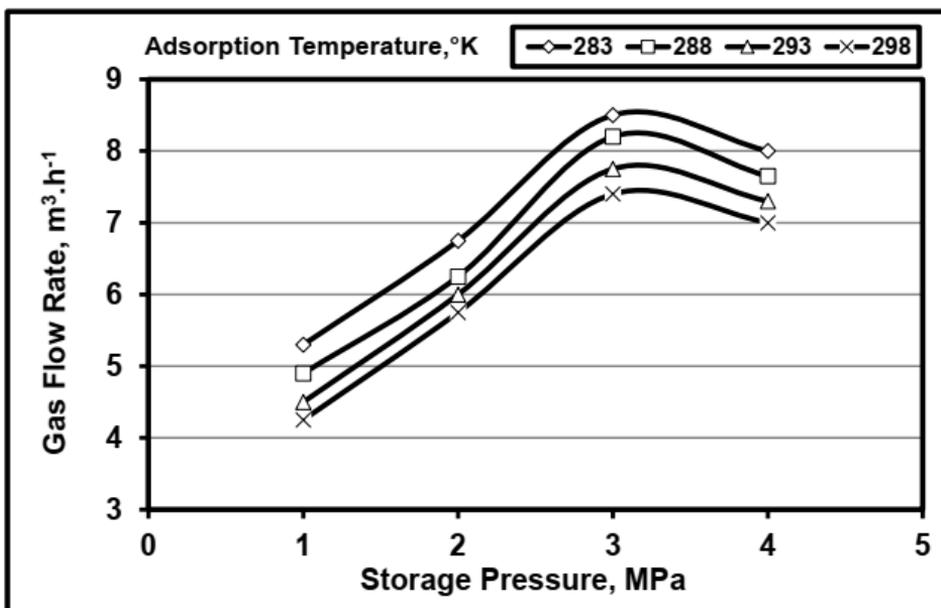
Fig. 5: Effect of adsorption pressure and temperature on gas flow rate.

Results show that increasing storage pressure increased volumetric flow rates in porous media inside activated carbon up on 3 MPa any further increase in storage pressure up to 4 MPa gas flow rates will decrease as a result of the reduced volume of adsorbed gas, the high pressure does not allow the methane molecules to take sufficient time until the adsorption process is done during the experimental conditions.

Wobbe Index

Results obtained show that Lower Wobbe Index was 48.12 MJ.m^{-3} for biomethane compared to 47.20 MJ.m^{-3} for natural gas. Biomethane gas has a larger Wobbe Index so will be delivered larger amount of energy compared to natural gas at the same operating pressure.

Energy production and net energy output

Energy production as well as net energy output are too related to storage pressure and adsorption temperatures as shown in Figs. 6 and 7. The experimental results showed that energy production and net energy output increased with increasing storage pressure up to 3 MPa, any further increase in pressure up to 4 MPa energy production will decrease, on the other hand results obtained show that decreasing adsorption temperature increased values of both energy production and net energy output.
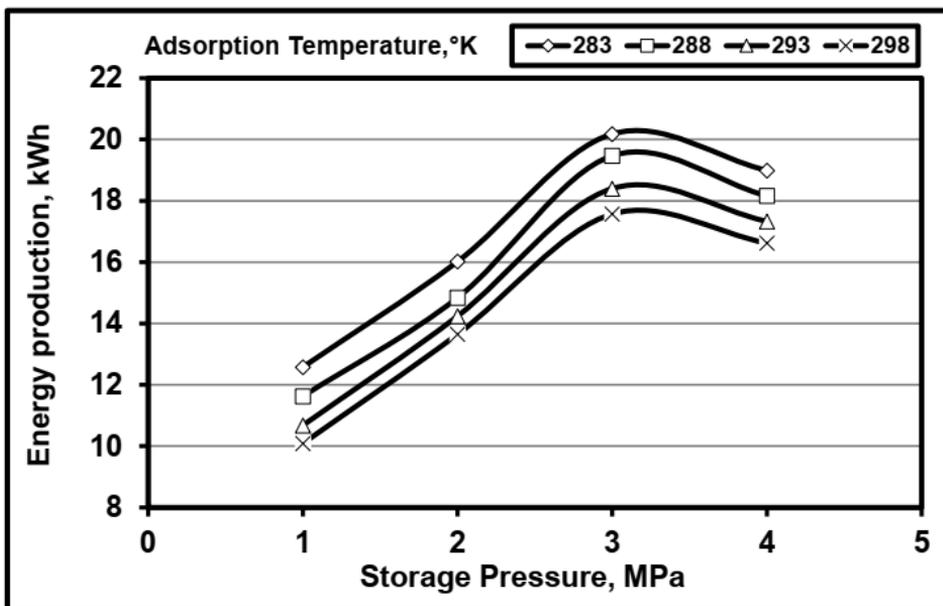
Fig. 6: Energy production as a function of pressure and temperature.

It was noticed that the energy production values were (17.57, 18.40, 19.47 and 20.18 kWh) and values of the net energy output were (16.28, 17.11, 18.18 and 18.89 kWh) measured at adsorption temperatures of 298, 293, 288 and 283 °K respectively and under storage pressure of 3 MPa.
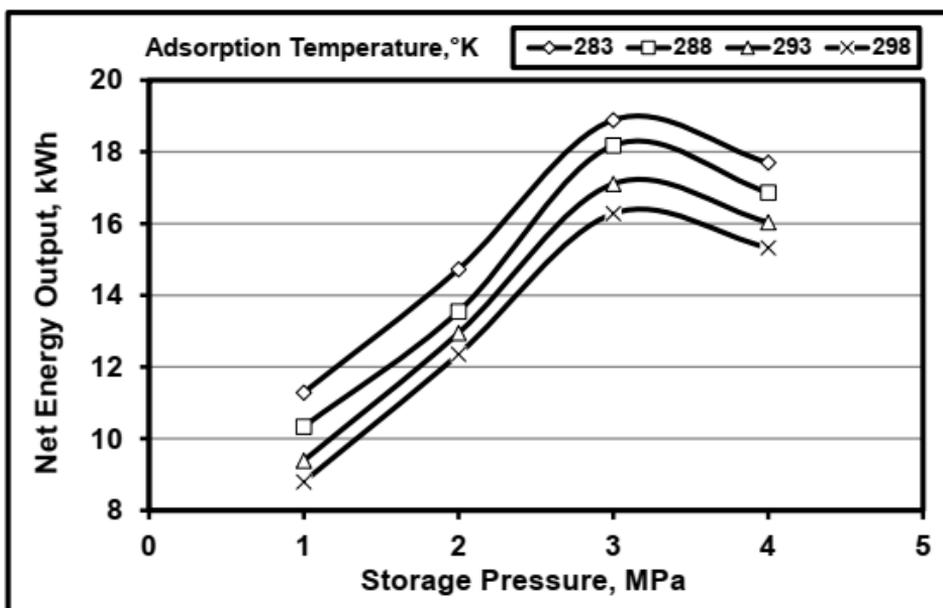
Fig. 7: Net energy output as a function of pressure and temperature.

While the values of the energy production were (10.09, 10.68, 11.63 and 12.58 kWh) and values of the net energy output were (8.80, 9.39, 10.34 and 11.29 kWh) under the same pervious temperatures respectively and at storage pressure of 1 MPa. An AMG storage technique leads to the added thermal load of the adsorbent material, an activated carbon often has moderate to poor the thermal conductivity. Therefore, an energy production as well as net energy output of an AMG system is more significantly affected by the flow rate due to the thermal effects under different pressure levels. It should be noted that both higher and lower values of storage pressure more or less than the optimum value tend to decrease energy production as well as net energy output due to the decrease in gas flow rates.

Energy balance for treatment system

The energy balance concept of any renewable energy generation system is a notable factor to determine whether the system provided can be applied or not. In this study, the net energy balance take into was considered for an adsorbed gas storage system is shown in Table 3.

Table 3: Shows energy balance for the biogas treatment system

Storage pressure, MPa	1	2	3	4
Compression Ratio	9.87	19.74	29.62	39.49
Actual density, kg.m^{-3} at 283 °K	6.83	13.65	20.49	27.31
Compressibility Factor	0.995	0.995	0.995	0.995
Lower Wobbe Index, MJ.m^{-3}	48.12	48.12	48.12	48.12
Energy Consumption, kWh	1.29	1.29	1.29	1.29
Energy production, kWh at 283 °K	١٢,٥٨	١٦,٠2	٢٠,١٨	18.99
Net Energy Output, kWh at 283 °K	11.29	14.73	18.89	17.70

In case the net energy output of the system is positive then the presented system be applicable option and vice versa. Furthermore, Table 3 presents also compression ratio, actual density and compressibility factor. Based on these data the energy balance or net energy output of the adsorbed gas storage system can be obtained. Net energy output of the designed system reaches to 18.89 kWh an energy positive at a storage pressure of 3 MPa and an temperature of 283°K. Accordingly, this technology represents one of the potential green energy or renewable energy resources from the sustainable development perspective. This would therefore reduce and possibly replace traditional energy and reduce adverse environmental

impacts. Current approach aids estimation of resource volume as well as allows direct comparison with gas yield from other systems.

4. CONCLUSION

The storage of methane gas, either in quantities or in density, plays a vital role for its use in many industrial applications. The proposed alternative is to increase the energy density by using adsorbed methane gas (AMG) storage technique as one of the solutions suggested in this regard. The obtained results strongly suggested that the heat of adsorption should be controlled by tubular heat exchanger to prevent temperature change in the adsorbent bed. The performance of the adsorption system was measured under four different pressures (1, 2, 3, and 4MPa) and adsorption temperatures (283, 288, 293 and 298°K). It was noticed that the highest values of storage capacity, adsorption efficiency, and net energy output were (170 V/V, 94.40% and 18.89 kWh) respectively, at pressure of 3 MPa and adsorption temperature 283 °K.

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الملخص العربى

نظام تخزين غاز الميثان الممتز باستخدام الكربون الحبيبي المنشط

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تتضـــح أهميـة الطـاقـة المتجـددة في عمليـة التنميـة وارتبـاطهـا الوثيق بمختلف مجـالات التنميـة المسـتدامة. ويعتمد العالم على مصـــادر الطاقة التقليدية والمتمثلة فـــــي كل من البترول والغاز الطبيعي بالرغم من محدوديـة الاحتياطيـات المتوفرة من هذه المصـادر والتي لا تتناسب مطلقًا مع معدلات زيادة استهلاك الطاقة ، الوضع الذى يهدد من أمن الطاقة واستدامتها.

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ولذلك تسعى دول العالم ولاسيما مصر إلى وضع إستراتيجيات جديدة نحو مصادر الطاقة الجديدة والمتجددة كمصدر تكميلي لمصادر الطاقة التقليدية في الوقت الحاضر والمستقبل وذلك لتلبية الاحتياجات المتزايدة من الطلب على الطاقة. على الرغم من وجود دراسات حول إنتاج ومعالجة الغاز الحيوى ولاسيما عملية الضغط والتخزين ، إلا أن هذه الدراسات قد تناولت تكنولوجيا الغاز الحيوى فى ضوء الطور الغازى الأمر الذى جعل السعة التخزينية محدودة بكثافة طاقة منخفضة تحت مستويات ضغط عالية والتي تشكل تحدياً لبعض التطبيقات. كما تشوب هذه الطريقة خطر الضغوط والحرارة العالية داخل اسطوانة التخزين مما يتطلب اتخاذ بعض الاحتياطات اللازمة كاختيار اسطوانات ذات مواصفات محددة مع وضع صمامات أمان معقدة ومن هنا تكمن المشكلة.

لذلك ، تناولت هذه الدراسة طريقة جديدة كنظام تخزين غاز الميثان الممتز (AMG) ، تعد هذه التقنية بديلاً حديثًا تنافسياً وقابل للتطبيق لمقدرته على تخزين الطاقة بكثافة عالية ومستويات ضغط منخفضة والذى لا يتوافرمع الطرق الأخرى (الدراسات السابقة) وتعتمد هذه التكنولوجيا على استخدام الكربون المنشط لتخزين الغاز بالقرب من الطور السائل (حالة الامتزاز) من خلال مسامية الكربون التى تعزز السعة التخزينية للغاز بشكل كبير.

ولتحقيق هدف الدراسة تم اختيار مبادل حراري أنبوبي بمساحة سطحية ٤٠٠ سم² وفاقد فى الضغط بقيمة ٣٦,١٢ كيلوباسكال بعد عمل الحسابات اللازمة لذلك لمنع تغير درجة الحرارة في طبقة الممتزات ولتسهيل نقل الحرارة من خلال الحمل الحراري القسري وبالتالي تحقيق نظام تخزين فعال بسعة تخزينية وكثافة طاقة عالية تحت ظروف التشغيل المختلفة.

اشتملت الدراسة على استخدام اسطوانة التخزين والمعبأة بالكربون المنشط ، وحدة تنقية الغاز ، ضاغط الغاز ومتصل به دائرة التشغيل الكهربائية ، منظم وصمام تخفيف الضغط ، مقياس الضغط ، صمام خروج الغاز ، المبادل الحراري والمزود بوحدة التحكم الإلكترونية بعد تصميم الدائرة الخاصة بها واختيار المكونات ووضعها فى جدول خاص بذلك تحت شدة تيار الحمل وجهد التشغيل ٢٣٠ فولت. حيث تم تخزين غاز الميثان بنسبة ٩٥% بعد عملية التنقية بالقرب من الطور السائل تحت مستويات ضغوط منخفضة بقيمة (١ ، ٢ ، ٣ و ٤ ميجاباسكال) ودرجات حرارة تبلغ (٢٨٣ ، ٢٨٨ ، ٢٩٣ و ٢٩٨ درجة كلفن) وتم تقييم أداء النظام المطور بأخذ القياسات التالية:

سعة التخزين ، كفاءة الإمتزاز ، معدل تدفق الغاز وإنتاج الطاقة ، وكذلك صافي إنتاج الطاقة (توازن الطاقة). وقد اتضح من النتائج التجريبية العلاقة الوثيقة بين كل من ضغط التخزين ودرجة حرارة الامتزاز ومن ثم أمكن تحسين الطاقة المتولدة تحت ظروف التشغيل المختلفة. فقد سجلت النتائج المتحصل عليها أن أعلى سعة تخزينية بلغت ١٧٠ حجم/حجم ومعدل تصرف ٨,٥٠ م³.س⁻¹ بكفاءة ٩٤,٤٠% أي ما يعادل ١٨,٨٩ كيلوواط ساعة صافي إجمالى الطاقة المتولدة عند ضغط ٣ ميجاباسكال ودرجة حرارة امتزاز ٢٨٣ درجة كلفن.