A new physisorption power generation system using advanced adsorbent materials

Fadhel Noraldeen Al-Mousawi 1, Raya Al-Dadah 2, and Saad Mahmoud 2
1 Department of Mechanical Engineering, University of Karbala, Karbala, Iraq
2 Department of Mechanical Engineering, University of Birmingham, B15 2TT, United Kingdom
fadhelnor@gmail.com, fadhal.nor@uoberbala.edu.iq (Corresponding author F.N. Al-Mousawi)

Abstract

A large number of people worldwide lack access to secure power systems, particularly in developing countries. The abundant solar energy and waste heat energy can be used to generate electric power cleanly using absorption and physisorption systems to build small localized power generation units. The inclusion of a turbine within the physisorption system opens great opportunities to use low-grade and medium-grade heat sources, such as solar energy, geothermal energy and industrial waste heat, for power generation. In this numerical study, the water adsorption system for cooling and electricity (ASCE) is utilized for the first time to generate electric power only using advanced metal organic framework (MOF) materials. The main components of the physisorption power generation cycle (PPGC) are similar to those of ASCE, where the only difference is in the applied operating conditions. In PPGC, the water temperature entering the evaporator is relatively high, so that no cooling effect within the normal range can be obtained. This helps to increase the adsorption uptake in some adsorbent materials like MIL101-Cr, which increases the mass flow rate of the working fluid and improves the power generation process. According to these considerations, the two-bed PPGC system adopted in this study can generate electricity of up to 5.24 kW utilizing about 14.28 kg of MIL101-Cr with heating temperature of 320 °C. This study highlights the potential of using advanced physical adsorbent materials like MOFs (e.g. MIL101-Cr) in power generation utilizing two-bed PPGC under a range of operating conditions.

1. Introduction

Today, humanity faces a major challenge; that of meeting the large increase in energy demand where the world energy consumption is likely to increase by up to 56% in 2040 [1]. The problem is worse in hot climate regions where cooling equipment consumes great amounts of electric power. At present, power generation still depends mainly on fossil fuels which leads to serious global issues and more carbon emissions. The large quantities of low-grade and medium-grade heat sources like solar energy and industrialised waste heat can effectively generate electric power using promising green technologies such as the organic Rankine cycle (ORC), absorption and physisorption systems. ORC and the Kalina Cycle (KC) are clean technologies that generate electric power utilising low and medium grade heat sources [2, 3].

The Kalina cycle is considered as the classic sorption power generation cycle, and was introduced in the 1980s [4]. It was followed by a wealthy family of Kalian cycle system (KCS) [5]. The Goswami cycle (another sorption cycle) was proposed in 1995 to produce cooling and electric power at the same time. It is a combination of an ammonia-water absorption cycle and an ammonia-based Rankine cycle [6]. Many researchers were interested in the new power generation cycles. Wang et al [7] numerically studied the performance of Kalina cycle in order to improve the cycle’s efficiency using the method of sliding condensation pressure. The condenser pressure is adjusted according to ambient temperature with various ammonia-water concentrations. Results showed that the annual average thermal efficiency can be improved significantly, compared to a conventional Kalina cycle. Long et al
[8] studied the exergy efficiency and performance optimization of Kalina cycle system 11 (KCS-11) utilising a low-grade heat source. The study considered the effect of evaporator pressure and ammonia-water concentration on the overall performance. Results showed that there are optimum evaporator pressures leading to the maximum external internal exergy efficiencies. Also, results showed that external exergy efficiency is slightly affected by ammonia concentration.

A number of researchers have investigated the feasibility of generating electric power and cooling at the same time using absorption technology [9, 10], while others have studied the possibility of generating refrigeration and electric power simultaneously using chemical adsorbent materials [11, 12] and physical adsorbent materials [13-17]. Bao et al [2] carried out theoretical thermodynamic assessments of a chemisorption power generation system powered by low-grade heat sources and compared results to the ORC cycle. The pumpless ORC system has more efficiency than that of the chemisorption power generation system however, the latter was superior on energy density which is at least twice more than that of the pumpless ORC system. Also, Bao et al [18] studied and optimised a thermodynamic model of the chemisorption power generation cycle utilising MnCl2–NaBr, MnCl2–SrCl2, and SrCl2–NaBr as sorbent pairs. Results showed that efficiency is increased by up to 4.5 times and the exergy efficiency is enhanced by up to 8.3 times utilising a heating temperature of 200 ºC. Bao et al [19] have suggested and investigated a new chemisorption power generation cycle with multi-stage expansion and heating temperature ranging from 30 to 150 ºC. Results showed that thermal efficiency can reach up to 15% when 2–4 expansions are used. Chemical adsorbents have practical problems, like agglomeration and swelling. Physical adsorbents are more stable and can keep their original properties after desorption/adsorption process; consequently, they are commonly used in commercial systems.

Recently, adsorption systems based on physical adsorbent materials (physisorption systems) have gained more attention especially after introduction of the metal organic frameworks (MOFs) which are considered as new materials with very high porosity, large surface area of up to 5500m²/g, and uniform pore size. MIL101-Cr MOF has exhibited a superior water uptake of 1.4 kg/kg dry adsorbent, considerably higher than commercial adsorbent materials [13, 20]. Power generation cycle (PPGC) has a similar configuration of adsorption system for cooling and electricity (ASCE) [13, 14] which consists of two desorber/adsorber, condenser and evaporator, in addition, an expander which is incorporated to generate electric power.

In this paper, we use – for the first time – physical adsorbent materials to generate electric power using the same configuration of ASCE, utilising advanced adsorption materials such as MOF MIL101-Cr. Thus, the performance of PPGC is investigated to produce electric power.

2. Adsorption system for cooling and electric power

Figure 1 shows a schematic diagram of an adsorption system for cooling and electric power (ASCE) which utilises physical adsorbent materials like silica-gel and AQSOA-Z02 and consists primarily of two adsorbent beds, condenser, evaporator and expander (turbine). The system was reported by [13, 14, 16].

The expander (turbine) is placed between the high-pressure (also with high-temperature) adsorbent bed and the condenser, which has relatively low pressure. Electricity can be generated as a result of the hot steam that passes through the expander (turbine) and expands from the maximum cycle pressure generated in the hot-bed to the condenser pressure. In the condenser, the hot steam is cooled using external cooling water, while the condensate passes to the evaporator to start a new adsorption cycle.

Although the system can generate cooling and electric power concurrently utilizing low-grade heating sources, the power generation can be increased when the evaporator temperature is increased when some adsorbent materials with superior water uptake, like MOF MIL101-Cr, are used. This is as a result of increasing the water uptake and then the mass flow rate passing through the expander.
Figure 1: ASCE system for cooling and electric power adopted by [13]

3. Physisorption power generation cycle (PPGC)

The physisorption power generation cycle (PPGC) is similar to the adsorption system for cooling and electricity (ASCE) and the only difference is in the applied operating conditions. In PPGC, the fluid temperature entering the evaporator is comparatively high, so that no cooling is achieved in the evaporator and electricity is the only product that is generated from this system. The new operating conditions help to increase the adsorption uptake in some adsorbent materials, like MIL101-Cr, which increases the mass flow rate of water and increases the value of power generation. To define the energy balance in the adsorbent beds, the temperature is assumed to be constant using the lumped parameter method [13, 16, 21-24].

\[(MC_p)_{bed, eff} \frac{dT_{bed}}{dt} + (M_a x_{cp}) \frac{dT_{bed}}{dt} = \varphi M_a \left( \frac{dx}{dt} \right) (Q_{st}) - \left( \dot{m} C_p \right) \left( T_{j,o} - T_{j,in} \right) \] (1)

Water temperature at the adsorbent bed outlet can be calculated as [13, 16, 21, 24].

\[T_{j,o} = T_{j,bed} + (T_{j,in} - T_{j,bed}) \exp \left[ \frac{-(UA)_{bed}}{(\dot{m} C_p)} \right] \] (2)

Energy balance in the evaporator can be calculated as [13, 16, 25-27].
\[
\frac{d}{dt}(MC_p)_{\text{evap,eff}} = \phi hfgM_a \frac{dx_{\text{ads}}}{dt} - (\dot{m}c_p)_{\text{evap}}(T_{\text{chill,o}} - T_{\text{chill,in}}) - (c_p)w(T_{\text{cond}} - T_{\text{evap}})M_a \frac{dx_{\text{des}}}{dt}
\]

(3)

The water temperature at the evaporator outlet is calculated as [13, 16, 25, 26, 28].

\[
T_{\text{chill,o}} = T_{\text{evap}} + (T_{\text{chill,in}} - T_{\text{evap}})\exp\left[-\frac{(UA)_{\text{evap}}}{(\dot{m}c_p)_{\text{evap}}}\right]
\]

(4)

Mass balance is written as [13, 16, 21, 24, 25, 28].

\[
\frac{dM_{\text{ref}}}{dt} = -M_a \left[\frac{dx_{\text{des}}}{dt} + \frac{dx_{\text{ads}}}{dt}\right]
\]

(5)

Energy balance equations for the condenser can be written as [13, 16, 25-27, 29].

\[
\frac{d}{dt}(MC_p)_{\text{cond,eff}} = \phi hfgM_a \frac{dx_{\text{des}}}{dt} - (\dot{m}c_p)_{\text{cond}}(T_{w,o} - T_{w,in}) - (c_p)w(T_{\text{exp}} - T_{\text{cond}})M_a \frac{dx_{\text{des}}}{dt}
\]

(6)

The water temperature at the condenser outlet can be calculated as [13, 16, 25, 26].

\[
T_{w,o} = T_{\text{cond}} + (T_{w,in} - T_{\text{cond}})\exp\left[-\frac{(UA)_{\text{cond}}}{(\dot{m}c_p)_{\text{cond}}}\right]
\]

(7)

The mechanical power generated by the turbine is calculated as [16]:

\[
W_{\text{exp}} = \int_{t_0}^{t_{\text{cycle}}} m_{\text{ads}}dh_{\text{dt}}
\]

(8)
Specific power output is calculated as [16]:

$$SP = \frac{\int_{t_{cycle}}^{t_{cycle}} m_{ads} \Delta h dt}{M_{a}t_{cycle}}$$

(9)

where, $\Delta h$ denotes to the enthalpy difference (J/kg).

Thermal efficiency (adsorption power efficiency) is defined as the ratio of the power generated in the expander to the heat supplied and it can be written as [16]:

$$\eta_{th} = \frac{\int_{t_{cycle}}^{t_{cycle}} m_{ads} \Delta h dt}{(\dot{m}c_{p})_{h} \int_{0}^{t_{cycle}} (T_{h,in}-T_{h,o}) dt}$$

(10)

Also, exergy efficiency is calculated as [30, 31]:

$$\eta_{ex} = \frac{\int_{t_{cycle}}^{t_{cycle}} m_{ads} \Delta h dt}{E_{in}}$$

(11)

where

$$E_{in} = \frac{\int_{0}^{t_{cycle}} [(h_{h,in}-h_{h,o})-T_{amb}(s_{h,in}-s_{h,o})] dt}{t_{cycle}}$$

(12)

4. Results and discussion

Table 1 illustrates the main operating conditions applied in this study, including heating fluid temperature coolant temperature and cycle time. Table 2 illustrates the main physical characteristics of the absorbent materials used in this study. To validate the numerical model used in our research, a comparison between numerical (from this study), and experimental results [32] for the temperatures of the adsorbent beds, condenser and evaporator utilizing silica-gel/water as a working pair has been made and is shown in Figure 2. The comparison shows good agreements between the numerical and experimental results.

Figure 3 shows the electric power generated by PPGC using MIL101-Cr and AQSOA-Z02, with heating temperature varying between 160 and 320 °C. It is clear that the amount of electricity generated by MIL101-Cr is more 2.5 times of that of AQSOA-Z02, and this is due to the high water uptake for MIL101-Cr at these operating conditions. Maximum power output is more than 4 kW using a heating temperature of 320 °C.
Table 1. Main operating conditions applied in this study

| Characteristic                          | Value               |
|----------------------------------------|---------------------|
| Heating fluid temperature (°C)         | 320                 |
| Cooling fluid temperature (°C)         | 26                  |
| Evaporator temperature (°C)            | 46                  |
| Mass flow rate - heating fluid (kg/s)  | 0.3                 |
| Mass flow rate - cooling fluid (kg/s)  | 0.8                 |
| Mass flow rate - condenser (kg/s)      | 0.8                 |
| Mass flow rate - evaporator (kg/s)     | 0.8                 |
| Half cycle time (s)                    | 450                 |
| Switching time (s)                     | 20                  |

Table 2. Characteristics of the adsorption materials

| Characteristic          | AQSOA-Z02 | MIL101-Cr |
|-------------------------|-----------|-----------|
| Surface area (BET) m²/g | 590 [33]  | 3460 [34] |
| x kg/kg ads             | 0.2901 [35]| 1.4773 [35]|
| ρ kg/m³                 | 715.3 [35]| 620 [36]  |
| Qₛ (kJ/kg)              | 3420 [33] | 2557 [37] |

Figure 2. Validation of the numerical model against experimental data from [32]
Figure 3. Power generation from PPGC utilising AQSOA-Z02 and MIL101-Cr with range of heating temperature

Figure 4 shows the specific power (the amount of the electric power generated per one kilogram of the adsorbent material used in the system) that is generated by PPGC using MIL101-Cr and AQSOA-Z02 with a heating temperature varying between 160 and 320 ºC. Results show that specific power of MIL101-Cr is much higher than that of AQSOA-Z02, due to the high water uptake that is obtained when using MIL101-Cr at these operating conditions. That means more mass flow rate generates in the adsorbent bed and more power is generated in the expander. Figure 5 shows the thermal efficiency of PPGC with MIL101-Cr and AQSOA-Z02 using heating temperature ranging between 160 and 320 ºC. Generally, as the heating fluid temperature increases, the thermal efficiency increases, however, MIL101-Cr shows higher thermal efficiency than that of AQSOA-Z02, and this is due to the high water uptake that is obtained when using MIL101-Cr. For MIL101-Cr, the thermal efficiency starts to decrease after the heating temperature of 280 ºC and this is due to high rate of energy consumption in the adsorbent bed. Results show that a maximum efficiency of about 9% can be achieved.

Figure 6 shows the exergy efficiency of PPGC using MIL101-Cr and AQSOA-Z02 with the same range of heating temperature. Generally, for both materials, as the heating temperature increases, the exergy efficiency increases, however, MIL101-Cr shows higher exergy efficiency than that of AQSOA-Z02. Also, the exergy efficiency of MIL101-Cr increases (with heating temperature) at a higher rate than that of AQSOA-Z02. Results shows that a maximum exergy efficiency of 25.6% is achieved at 160 ºC using MIL101-Cr.
Figure 4. Specific power of PPGC utilising AQSOA-Z02 and MIL101-Cr with range of heating temperature

Figure 5. Thermal efficiency of PPGC utilising AQSOA-Z02 and MIL101-Cr with range of heating temperature
Figure 6. Exergy efficiency of PPGC utilising AQSOA-Z02 and MIL101-Cr with range of heating temperature

Figure 7 and Figure 8 show the effect of using evaporator temperature ranging from 40 to 58 ºC (which is likely to be available naturally in countries with hot climates, especially in summer) on power output and specific power of PPGC for the cases of MIL101-Cr and AQSOA-Z02. As the evaporator temperature increases, both power output and specific power increases for MIL101-Cr, while they are not affected for AQSOA-Z02. This is because of the S-shape isotherms of the MIL101-Cr. Maximum power output and specific power of 5.2 kW and 366.5 W/kg_{ads} respectively can be achieved with an evaporator temperature of 58 ºC.

Figure 7. Effect of evaporator temperature on power generated from PPGC utilising AQSOA-Z02 and MIL101-Cr
Figure 8. Effect of evaporator temperature on specific power of PPGC utilising AQSOA-Z02 and MIL101-Cr

Figure 9 and Figure 10 show the effect of using evaporator temperature ranging from 40 to 58 ºC on the thermal efficiency and the exergy efficiency of PPGC for MIL101-Cr and AQSOA-Z02. For MIL101-Cr, as evaporator temperature increases, both thermal and exergy efficiencies increase, while they are not affected for AQSOA-Z02 as the water uptake is not affected by the partial pressure during the adsorption process.

Figure 9. Effect of evaporator temperature on thermal efficiency of PPGC utilising AQSOA-Z02 and MIL101-Cr
5. Conclusion

In this paper, the physisorption power generation cycle PPGC is used for the first time to generate electricity only using water adsorption technology and utilising low to medium grade heat sources. Two advanced adsorbent materials, namely AQSOA-Z02 and MIL101-Cr, are used in order to examine their ability to generate electric power.

The main results of this work are:

1. Generating electric power using a water physisorption power generation PPGC system is feasible.
2. MOF MIL101-Cr is considered a suitable adsorbent material for PPGC, where it generates about 2.5 times more electric power than AQSOA-Z02.
3. Maximum power output of 5.23 kW is achieved using about 14.28 kg of MIL101-Cr.
4. Maximum thermal efficiency and exergy efficiency of 9.2% and 21.6% can be achieved respectively utilising MIL101-Cr with hot bed temperature of 320 °C and evaporator temperature of 58 °C.
5. As heating source temperature increases, power output, thermal and exergy efficiencies increase for both AQSOA-Z02 and MIL101-Cr.
6. As evaporator temperature increases, power output, thermal and exergy efficiencies increase for MIL101-Cr, while they are not affected for AQSOA-Z02.

Nomenclature

Symbols

\( C_p \) \hspace{1cm} \text{Specific heat at constant pressure, (J/kg/K)}
\( h \) \hspace{1cm} \text{Enthalpy, (J/kg)}
\( h_{fg} \) \hspace{1cm} \text{Latent heat of evaporation (J/kg)}
\( M \) \hspace{1cm} \text{Mass, (kg)}
\( m \) \hspace{1cm} \text{Fluid mass flow rate, (kg/s)}
\( Q_{st} \) \hspace{1cm} \text{Adsorption isosteric heat, (J/kg)}
\( UA \) \hspace{1cm} \text{Overall conductance (W/K)}
\( SP \) \hspace{1cm} \text{Specific power (W/kg\text{ads})}
\( T \) \hspace{1cm} \text{Temperature, (K)}
\( t \) \hspace{1cm} \text{Time, (s)}
\( W \) \hspace{1cm} \text{Power (W), work (J/kg)}
\( x \) \hspace{1cm} \text{Water uptake, (kg/kg\text{ads})}
\( x_{eq} \)  
Equilibrium water uptake, (kg/kg)

**Greek letters**

\( \eta \)  
Efficiency

\( \rho \)  
Density kg/m\(^3\)

\( \varphi \)  
Flag

**Subscripts**

ads, a  
adsorbent

ads  
adsorption

amb  
ambient temperature

bed  
adsorbent bed

chill  
chilled water

cond  
condenser

des  
desorption

eff  
effective

evap, e  
evaporator

exp  
deriver

ex  
exergy

in  
inlet

j  
heating/cooling source

h  
heat source

o  
outlet

s  
saturation

w  
water

**Abbreviations**

ASCE  
Adsorption system for cooling and electricity

MOF  
Metal Organic Framework

MOFs  
Metal Organic Frameworks

PPGC  
Physisorption power generation cycle

**Acknowledgement**

The authors would like to acknowledge The Iraqi Ministry of Higher Education and Scientific Research for sponsoring this work.

**References**

[1] EIA. International Energy Outlook 2013. US Energy Information Administration 2013.

[2] Nemati A, Nami H, Ranjbar F, Yari M. A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery: A case study for CGAM cogeneration system. Case Studies in Thermal Engineering. 2017;9:1-13.

[3] Yue C, Han D, Pu W, He W. Comparative analysis of a bottoming transcritical ORC and a Kalina cycle for engine exhaust heat recovery. Energy Conversion and Management. 2015;89:764-74.

[4] AI K. Combined cycle and waste-heat recovery power systems based on a novel thermodynamic energy cycle utilising low temperature heat for power generation. ASME Paper. 1983;83-JPGC-GT-3.

[5] Zhang X, He M, Zhang Y. A review of research on the Kalina cycle. Renewable and Sustainable Energy Reviews. 2012;16:5309-18.

[6] DY G. Solar thermal power-status of technologies and opportunities for research. Proceedings of the second ISHMT-ASME heat and mass transfer conference. New Delhi: Tata: McGraw Hill, Suratkal, India; 1995.
[7] Wang E, Yu Z, Zhang F. Investigation on efficiency improvement of a Kalina cycle by sliding condensation pressure method. Energy Conversion and Management. 2017;151:123-35.

[8] Rui Long ZK, Baode Li, Zhichun Liu, Wei Liu. Exergy analysis and performance optimization of Kalina cycle system 11 (KCS-11) for low grade waste heat recovery 10th International Conference on Applied Ener. Hong Kong, China Elsevier; 2019.

[9] Parikhani T, Ghaebi H, Rostamzadeh H. A novel geothermal combined cooling and power cycle based on the absorption power cycle: Energy, exergy and exergoeconomic analysis. Energy. 2018;153:265-77.

[10] Ventas R, Lecuona A, Vereda C, Rodriguez-Hidalgo MC. Performance analysis of an absorption double-effect cycle for power and cold generation using ammonia/lithium nitrate. Applied Thermal Engineering. 2017;115:256-66.

[11] Bao H, Wang Y, Charalambous C, Lu Z, Wang L, Wang R, et al. Chemisorption cooling and electric power cogeneration system driven by low grade heat. Energy. 2014;72:590-8.

[12] Bao H, Wang Y, Roskilly AP. Modelling of a chemisorption refrigeration and power cogeneration system. Applied Energy. 2014;119:351-62.

[13] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Low grade heat driven adsorption system for cooling and power generation with small-scale radial inflow turbine. Applied Energy. 2016;183:1302-16.

[14] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Low grade heat driven adsorption system for cooling and power generation using advanced adsorbent materials. Energy Conversion and Management. 2016;126:373-84.

[15] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Integrated adsorption-ORC system: Comparative study of four scenarios to generate cooling and power simultaneously. Applied Thermal Engineering. 2017;114:1038-52.

[16] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Different bed configurations and time ratios: Performance analysis of low-grade heat driven adsorption system for cooling and electricity. Energy Conversion and Management. 2017;148:1028-40.

[17] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Novel system for cooling and electricity: Four different integrated adsorption-ORC configurations with two expanders. Energy Conversion and Management. 2017;152:72-87.

[18] Bao H, Ma Z, Roskilly AP. An optimised chemisorption cycle for power generation using low grade heat. Applied Energy. 2017;186:251-61.

[19] Bao H, Ma Z, Roskilly AP. A chemisorption power generation cycle with multi-stage expansion driven by low grade heat. Energy Conversion and Management. 2017;150:956-65.

[20] Fadhel Al-Mousawi RA-D, Saad Mahmoud. MIL101Cr MOF – Water Adsorption System for Cooling and Power Generation Using Waste Heat. SusTem2015. United Kingdom, Newcastle2015.

[21] Saha BB, Elisa C. Boelman, and Takao Kashiwagi. Computational analysis of an advanced adsorption-refrigeration cycle—improving cooling capacity. International Journal of Refrigeration. 2004;27:225-34.

[22] Miyazaki T, Akisawa A, Saha BB, El-Sharkawy II, Chakraborty A. A new cycle time allocation for enhancing the performance of two-bed adsorption chillers. International Journal of Refrigeration. 2009;32:846-53.

[23] Sadeghlu A, Yari M, Mahmoudi SMS, Dizaji HB. Performance evaluation of Zeolite 13X/CaCl2 two-bed adsorption refrigeration system. International Journal of Thermal Sciences. 2014;80:76-82.

[24] Tso CY, Chao CYH, Fu SC. Performance analysis of a waste heat driven activated carbon based composite adsorbent – Water adsorption chiller using simulation model. International Journal of Heat and Mass Transfer. 2012;55:7596-610.

[25] Farid SK, Billah MM, Khan MZI, Rahman MM, Sharif UM. A numerical analysis of cooling water temperature of two-stage adsorption chiller along with different mass ratios. International Communications in Heat and Mass Transfer. 2011;38:1086-92.

[26] El-Sharkawy II, AbdelMeguid H, Saha BB. Towards an optimal performance of adsorption chillers: Reallocation of adsorption/desorption cycle times. International Journal of Heat and Mass Transfer. 2013;63:171-82.
[28] Saha BB, Koyama S, Kashiwagi T, Akisawa A, Ng KC, Chua HT. Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. International Journal of Refrigeration. 2003;26:749-57.

[29] Hamamoto Y, Amanul Alam KC, Akisawa A, Kashiwagi T. Performance evaluation of a two-stage adsorption refrigeration cycle with different mass ratio. International Journal of Refrigeration. 2005;28:344-52.

[30] Zhang N, Lior N. Development of a Novel Combined Absorption Cycle for Power Generation and Refrigeration. Journal of Energy Resources Technology. 2007;129:254.

[31] Wang J, Wang J, Zhao P, Dai Y. Thermodynamic analysis of a new combined cooling and power system using ammonia–water mixture. Energy Conversion and Management. 2016;117:335-42.

[32] Saha BB, Boelman, E.C., Kashiwagi, T. Computer simulation of a silica gel-water adsorption refrigeration cycle the influence of operating conditions on cooling output and COP. ASHRAE Trans. 1995;101:348 – 57.

[33] Kayal S, Baichuan S, Saha BB. Adsorption characteristics of AQSOA zeolites and water for adsorption chillers. International Journal of Heat and Mass Transfer. 2016;92:1120-7.

[34] Elsayed E, Wang H, Anderson PA, Al-Dadah R, Mahmoud S, Navarro H, et al. Development of MIL-101(Cr)/GrO composites for adsorption heat pump applications. Microporous and Mesoporous Materials. 2017;244:180-91.

[35] Al-Mousawi FNA. Adsorption system for cooling and power generation using advanced adsorbent materials. Edgbaston, Birmingham, UK: University of Birmingham; 2018.

[36] Gao L, Li CY, Yung H, Chan KY. A functionalized MIL-101(Cr) metal-organic framework for enhanced hydrogen release from ammonia borane at low temperature. Chem Commun (Camb). 2013;49:10629-31.

[37] Ehrenmann J, Henninger SK, Janiak C. Water Adsorption Characteristics of MIL-101 for Heat-Transformation Applications of MOFs. European Journal of Inorganic Chemistry. 2011;2011:471-4.