Applicability of adsorption cooling/desalination systems driven by low-temperature waste heat

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Abstract. Environmental and economic factors have a very strong impact on technological development. Energy efficiency is one of the most important topics associated with new technologies and their improvements. Increasing restrictions are being imposed on energy consumption and pollutant emissions in many countries, especially in the European Union. At the same time, the whole energy sector is facing rapidly growing cooling demands. A cooling system based on sorption processes may be an interesting alternative, especially adsorption chillers which can be driven by heat at a temperature from 45°C. The application of this kind of systems has one more advantage: it enables seawater desalination for drinking and service water. The paper presents an overview of adsorption chillers applicability in polygeneration using low-temperature waste heat. The newest systems, their parameters and working conditions are described. Also, directions of current research focused on adsorption chillers with desalination function are demonstrated based on literature. A review of available adsorption chillers technologies, materials and exemplary research installations is also presented. The general conclusion is that adsorption cooling and desalination technology have a strong potential, especially in regions with limited drinking water resources and high cooling demands.

1. Introduction

The continuous technological progress, the industrial development as well as automation and mechanisation of processes are all closely related to the growing demand for energy. The development of technology requires increased energy investments; at the same time, the question of environmental protection is raised as well as emissions of pollutants and climatic changes caused by the energy sector where the main fuel for the production of electricity is coal [1]. Nowadays, the issue of energy efficiency appears in a lot of fields of life – from small household appliances, through heating and ventilation to industrial processes and commercial power generation [2-6].

Not without significance is also the growing world population, the rapid development of cities, shopping centres, services, etc. According to the predictions [7], the world population will grow from the current number of 7.6bn to nearly 10bn in 2050. Additionally, growing demand is observed with regard to heating comfort at homes and workplaces. At present, 15% of electricity generated worldwide is used for the needs of refrigeration and air conditioning [8]. On average, 45% of the total energy demand in buildings is used by air-conditioning installations [8]. The currently observed climatic changes are considered to be among the most significant reasons for the increase in cooling demand [9].
The growing population also determines the increase in food production and its effective storage. These changes result in rapidly increasing cooling demand. To some extent this demand can be covered by the renewable energy industry which is being developed nearly all over the world.

Utilisation of currently prevailing refrigeration systems based on mechanical compressors requires delivering large amounts of electricity in relation to the cooling capacity [10]. Renewable energy production in the form of PV panels, hydropower plants and wind turbines can support the operation of these installations but this does not solve the problem of the impact of low-boiling materials that are used in compressor units on the environment. In line with the Kyoto Protocol [1] and the Montreal Protocol [11] application of agents that contribute towards depletion of the ozone layer (ODP – Ozone Depletion Potential) and towards global warming (GWP – Global Warming Potential) is being systematically reduced [12].

Of all of the Earth’s aquatic resources, merely 0.5% is made up of available freshwater. The remaining 99.5% is made up of seawater and water in the form of ice. The climate is getting warmer and warmer and causes disturbances in the so far existing circulation of water in the nature – changes affect levels of waters in rivers and lakes, as well as the annual precipitation totals in the individual regions. These factors in connection with the growing population are leading to a worsening of the problem of access to drinking water, especially in the subtropical areas, and in the future also in large urban agglomerations worldwide (the increase in water requirement by 2050 is assessed at 55% relative to the 2000 level) [13].

When considering the issue of energy efficiency in commercial power generation and industry, it can be observed that a differentiation is being made between the values of the particular forms of energy. The most valuable electric power is used with very high efficiency of conversion into other forms of energy; and on the other hand, low-temperature heat is commonly regarded as useless. Despite only a small difference relative to the ambient temperature, waste heat is released into the environment in very large quantities.

Low-temperature waste heat from processes is the only redundant component in the above release. Its effective utilisation is possible through sorption devices. Creation of polygeneration and hybrid systems, which also take advantage of RES technologies, allows manufacturing a large number of useful products in combined subsystems [2,3,14,15]. Adsorption refrigeration systems make use of the process of evaporation and condensation. Application of technologies having water as the cooling agent enables desalination of seawater and at the same time utilisation of waste or redundant heat. This results in an increase in the primary energy ratio (PER), and consequently, a reduction in the consumption of non-renewable energy resources.

2. Adsorption hybrid systems
Cogeneration systems (CHP – Combined Heat and Power) enable simultaneous generation of electricity and heat. Heat can be used inter alia for heating, domestic hot water, heating swimming pools or industrial processes. Adsorption cooling devices are supplied with a heat flux that can come from a CHP system. The generation of cooling, heating and power is defined as trigeneration.

The operating principle of an adsorption cooling system (Figure 1) consists in evaporating the refrigerant in the evaporator at reduced pressure. The process takes place without the use of a mechanical compressor and takes advantage of the thermal effect of adsorption and desorption. The system operates on a cyclical basis, the processes of adsorption and desorption (bed regeneration) take place alternately. Vapours of the refrigerant from the evaporator are adsorbed in the adsorption bed, which is accompanied by generation of heat, which is absorbed by the cooling water. In order to enable further operation of the bed, it is necessary to remove the refrigerant (adsorbate) from the adsorbent (desorption). This process requires supplying heat from an external source. The refrigerant vapours that are released in the process of desorption are delivered to the condenser. In a closed system, the condensate from the condenser goes back to the evaporator. It is possible to use an adsorption chiller with an open system in which the refrigerator is water. Constant delivery of water from an external source results in generation of condensate that is void of the substances dissolved in the feedwater. In the case of feeding the system with saline water, an additional product apart from the cooling effect is desalinated water [16].
Figure 1. Two-bed adsorption cooling-desalination system [16].

The first hybrid systems utilising the adsorption refrigeration system provided the heating and cooling effects [17,18]. Numerous studies were conducted on the use of solar energy for powering adsorption systems [17-22]. Application of power from solar panels for powering adsorption refrigeration systems is cost effective and environmentally justified. The increased cooling demand during the year takes place in a period when the quantity of solar energy that can be utilised is also the greatest [18]. Application of the appropriate pair adsorbent-adsorbate also enables utilisation of waste heat from engine exhaust fumes [23].

3. Adsorption cooling and desalination working pairs
The key parameter determining the possibility of combining an adsorption refrigerator with a source of heat is the bed regeneration temperature. Regeneration temperatures below 90°C enable utilisation of heat from solar collectors and utilisation of network heat in the form of hot water [24]. Regeneration temperature is a parameter characteristic for each adsorbent. Beside the regeneration temperature, which determines the parameters of the source of heat, there are a number of other requirements that are applied to adsorbents [18]:

- high sorption capacity in relation to the mass for improved cooling capacity and reduced bed mass;
- low specific heat;
- high thermal conductivity contributing to the reduction of the cycle duration and improving the dynamics of the sorption processes;
- non-toxic, non-aggressive;
- low price.

High sorption capacity is closely related to the specific surface area, and thus also porosity. A large number of pores negatively affects the thermal conductivity of a material, which necessitates reaching a compromise between these two features [25].

In order to achieve a high efficiency of a refrigerator, the key issue is to match the appropriate adsorbate. It must work with the adsorbent through the appropriate size of molecules and at the same time fulfil the following requirements [18]:

- high latent heat in relation to the volume;
- high thermal conductivity;
- thermal stability within the range of operating temperatures of the adsorbent;
- low viscosity and specific heat;
- non-toxicity;
- low saturation pressure.
The working pairs most frequently described in the literature as well as their properties and applications have been presented in Table 1.

| Adsorbent - adsorbate       | Desorption temperature range | Adsorption heat, kJ/kg | Specific cooling power (SCP) | Application                  |
|-----------------------------|------------------------------|------------------------|------------------------------|------------------------------|
| Silica gel – water [18]     | Below 90°C                   | 1000–1500              | High                         | Air conditioning             |
| Activated carbon – Methanol [18] | Below 120°C                | 1800–2000              | Normal                       | Ice making                   |
| Activated carbon – Ammonia [18]    | Up to 150°C                 | 2000–2700              | Higher than silica gel       | Refrigeration / Ice making   |
| Activated alumina – water [26]    | 120–260°C                   | 2800–3000              | –                            | Desiccant cooling            |
| Zeolite – water [18]         | Up to 200°C                  | 3300–4200              | Normal                       | Air conditioning             |
| Zeolite – Ammonia [18]       | 150–200°C                    | 4000–6000              | High                         | Refrigeration / Ice making   |

The most commonly applied adsorbents include silica gel, activated carbon and zeolite. For water desalination, it is possible to use zeolite, silica gel and activated alumina. Among them it is silica gel that best fulfills the requirements described above but its price is higher [18]. The low desorption temperature allows for more common application and taking advantage of low-temperature heat. The operation of an adsorption chiller with silica gel-water working pair is possible from approx. 43°C for two-stage devices and 62°C for single-stage ones [27].

4. Adsorption cooling and desalination systems

The dynamic development of technology in the last decade has caused significant differences in the parameters achieved by different systems. Examples of new installations together with the most important indicators have been presented in Table 2. Values of SCP, SDWP and COP have been presented in relation to the temperature of the feeding source (HWIT – Hot Water Inlet Temperature) and the temperature of cooling water (CWIT – Cooling Water Inlet Temperature). Significant differences between SCP and SDWP values can be noticed. Mitra et al. [28] have developed a mathematical model for a two-stage installation, which they verified in an experiment and obtained a very high uniformity of results between the both analyses. The numerical model of installation designed by Thu et al. [29] has also displayed a good agreement with the experiment but the SDWP indicator reached a 10-fold greater value in this case. The analysis conducted by Alsaman et al. [30] indicates the widest range of results from among those presented below. Authors conducted simulations for various temperature conditions. The values of SCP, SDWP and COP show correlation with operating conditions, both in the simulation and in the experiment. The last example is an installation with commercially available with a chiller unit with cooling capacity of 90kW, supplied from a cogeneration system. Authors of the analysis [31] determined the coefficient of performance (COP); however, no data are available with regard to the cooling capacity in relation to the adsorbent mass.

| Ref | Year | Working pair | HWIT, °C | CWIT, °C | SCP, kW/tonne | SDWP, m³/tonne | COP | Details                  |
|-----|------|--------------|----------|----------|---------------|----------------|-----|--------------------------|
| [28] | 2017 | Silica gel – water | 85.0°C  | 24.0°C   | 30.2          | 0.96           | 0.28 | 2-stage, 4-bed            |
| [29] | 2017 | Silica gel – water | 70.0°C  | 7.0°C    | 12.3          | –              | 0.23 | 4-bed, int. heat recovery |
| [30] | 2017 | Silica gel – water | 85.0°C  | 30.0°C   | 112.0         | 4.0            | 0.46 | 2-bed, solar heat driven  |
|     |      |              | 85.0°C  | 25.0°C   | ~140          | 5.3            | ~0.50|                          |
|     |      |              | 85.0°C  | 15.0°C   | ~225          | 8.0            | ~0.55|                          |
| [31] | 2015 | Silica gel – water | 60.0°C  | 25.0°C   | 4.0           | –              | 0.642| 3-bed                    |
| [32] | 2016 | Silica gel – water | 85.5°C  | 29.5°C   | 125.0         | –              | 0.51 | 2-bed with optimized modular adsorbers |
|     |      |              | 85.4°C  | 30.3°C   | 86.4          | –              | 0.34 |                          |
The differences in values of the SCP, SDWP and COP for similar installations are significant and in the cases of systems [28] and [30] the difference in the SCP values that were achieved is almost 19-fold. The occurrence of such significant differences is results from different operating conditions and the design of the device. When analysing the operation conditions and the assumptions made by the researchers, it was noticed that the temperature of chilled water at the outlet and at the inlet is critical for the cooling capacity and thus the value of SCP. Furthermore, an essential role is played by the adjustment of the half cycle time (duration of adsorption/desorption including pre-cooling/pre-heating [28]) to the particular device. Of key importance for achieving the maximum cooling capacity per unit of adsorbent is that the device operates with half cycle time adjusted to the temperature of the heat source (Figure 2).

![Figure 2. Correlation between the value of SCC (SCC has the same meaning as SCP) and the half cycle time, and a curve of maximum SCC values [28].](image)

5. Directions of current research
A lot of researchers are currently involved in developing the adsorption technologies due to their advantages, such as utilisation of low-temperature heat, uncomplicated mechanical design, resistance to corrosion and silent operation. The main direction is creating and developing mathematical models and simulations, from the kinetics of the sorption processes and properties of adsorbents [30], through modelling cooling [33], and desalination systems [34], to hybrid systems [35]. Based on increasingly accurate models and simulations, new installations are created, adjusted to the operating conditions provided for in designs in terms of optimising their performance. Of crucial importance for the evaluation of the cooling and desalinating systems are the COP (Coefficient of Performance), SCP (Specific Cooling Power), representing cooling capacity in relation to the adsorbent mass, and SDWP (Specific Water Daily Production). The SCP indicator is essential due to the mass of sorption devices resulting from the large quantity of adsorbent. A large quantity of adsorbent compensates the effect of the thermal conductivity of the bed and sorption capacity on the performance of the device [36].

Improvement of the sorption properties is possible through modifications of the adsorbent properties as well as modifications in the bed design. A change in the adsorbent properties is possible e.g. by a modification of its composition. Freni et al. [37] modified silica gel by calcium nitrate and obtained COP higher by approx. 0.08 relative to the initial material, i.e. 0.51-0.71. Henniger et al. [38] addressed the problems of the stability of adsorbent properties and reduction of sorption capacity. It has been demonstrated that for silica gel the decrease is approx. 5% and the changes require a more detailed investigation.

Cooling capacity is also affected by thermal conductivity. Consideration was given to the effect of the size of the sorbent grains (silica gel) on the course of the process and the adsorption coefficient. White [39] has demonstrated in a CFD analysis that application of finer grains has a positive effect on
the adsorption process. In order to improve the thermal conductivity work is being carried out on the
design of the adsorption bed, inter alia by applying adhesives [40], and SorTech AG applies
exchangers with glued silica gel grains in the eCoo devices.

The directions of current research also concern combining systems into multi-stage ones [27,41] as
well as improvements and modifications of the thermodynamic cycle, e.g. internal heat regeneration
[35]. A lot of studies concern powering adsorption chillers with solar energy from collectors
[14,18,22,36,42]. However, another problem related to adsorption chillers is the varying cooling
capacity resulting from the cyclic character of operation. Attempts are made at achieving stable
capacity by shortening the adsorption cycle time, which is related to the rate of these processes, and by
using multiple beds. A solution is application of multi-bed systems [43-45]. In 2016 Kim et al. [46]
proposed controlling multi-bed adsorption an desalination unit by applying dephasing between two
consecutive adsorbers (ITL – Initial Time Lag). The adsorber cycles, displaced in phase, overlap and
so that the process runs continuously. This way of controlling enabled an increase in the daily yield of
desalinated water despite a decrease in the SDWP value. The distillate production curve has become
almost flat, like the COP and SCP. In 2015 Mitra et al. [47] commenced work on a control system for
cooling and desalinating units. The architecture that was developed was tested for a 4-bed system
working with silica gel but it can also work with 2- and 3-bed units. The operation of the device is
software controlled by means of actuators depending on the load, and the bed switching times are
appropriately adjusted.

6. Conclusion
Adsorption cooling systems are being dynamically improved. Their range of application is expanding,
and in combination with renewable energy sources they can make a cheap source of cooling.
Commercialisation of the solutions found in adsorption cooling industry is possible if the most
essential disadvantages are eliminated, i.e. the small cooling capacity in relation to the mass of the
installation and the fluctuations in the cooling performance resulting from the cyclic character of
operation. By coupling an adsorption refrigerator with the CHP system it becomes possible to make
use of the excess heat, which is of increasingly great importance due to the changing market demand
for heating and cooling. At present, new installations are created in which cooling is centrally
produced and then distributed to the end users. If the mass of the devices can be reduced then it will be
possible to apply adsorption refrigerators on site where small recipients have at their disposal a source
of heat, e.g. in the form of a micro-CHP system or solar installations.

Comparing to most popular cooling technology, i.e. compressor chillers, the negative impact on
environment of adsorption cooling systems is lower. On the other hand, the investment costs for
adsorption chillers are generally higher than for compressor systems. Economic aspect can be
improved with using waste heat from other processes. In such case, the cost of chilled water production
would be a result of chiller equipment needs, e.g. pumps, control units.

Undoubtedly, the possibility of desalinating water will greatly contribute to the commercialisation
of the technology. Countries that struggle with the shortage of potable water show interest in this
technology and launch programmes of financial support, e.g. the Kingdom of Saudi Arabia where a
scientific and research institution has been established at the King Abdullah University of Science and
Technology and its activity concerns the technology of adsorption desalination and cooling [48].

Acknowledgments
The first author acknowledges the support provided by Faculty of Energy and Fuels, AGH University
of Science and Technology, Cracow, Poland (15.11.210.400).

References
[1] Pikoń K, Kajda-Szcześniak M and Bogacka M, 2015 Przemysł Chemiczny 94 1548 (in Polish)
[2] Sztekler K, Komorowski M, Tarnowska M and Posak Ł, 2016 E3S Web of Conferences 10
(Cracow: SEED 2016)
[3] Sztekler K, Wojciechowski K, Komorowski M and Tarnowska M, 2016 E3S Web of
Conferences 14 (Cracow: Energy and Fuels 2016)
[4] Kyoto Protocol to the United Nations Framework Convention on Climate Change 1997
[5] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products OJ L 285
[6] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC OJ L 305
[7] Department of Economic and Social Affairs, Population Division 2015 World Population Prospects: The 2015 Revision, Key Findings and Advance Tables (New York: United Nations)
[8] Behede B, Wankhede U S, 2016 Int. J. of Latest Trend in Engineering and Technology 6 197
[9] Yun G Y and Steemers K, 2011 Appl. En. 88 2191
[10] Grisel R J H, Smeeing S F and De Boer R, 2010 Appl. Th. Eng. 30 1039
[11] United Nations Environment Programme Montreal Protocol on Substances that Deplete the Ozone Layer 1987
[12] Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2015 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 OJ L 150
[13] OECD 2012 Environmental Outlook to 2050 OECD Publishing
[14] Byrne P et al. 2015 Renewable and Sustainable Energy Rev. 47 703
[15] Calise F, Figaj R and Vanoli L, 2017 Energy Conversion and Management 149 798
[16] Alsaman A S, Askalany A A, Harby K, Ahmed M S, 2016 Renewable and Sustainable Energy Rev. 58 692
[17] Tchernev D I 1982 Proc. of the meeting of commissions E1–E2 (Jerusalem: International Institute of Refrigeration) p 209
Transfer 79 64

[41] Liu Y and Leong K C, 2006 *Int. J. of Refr.* 29 250
[42] Fadar A E, Mimet A and Perez-Garcia M, 2009 *Renewable Energy* 34 2271
[43] Thu K, Yanagi H, Saha B B and Ng K C 2013 *Int. J. of Heat and Mass Transfer* 65 662
[44] Thu K, Saha B B, Chakraborty A, Chun W G and Ng K C, 2011 *Int. J. of Heat and Mass Transfer* 54 43
[45] Mitra S, Srinivasan K, Kumar P, Murthy S S and Dutta P, 2014 *EnergyProcedia* 49 2261
[46] Kim A S, Lee H-S, Moon D-S and Kim H-J, 2016 *Desalination* 396 1
[47] Mitra S, Kumar P, Srinivasan K and Dutta P, 2016 *Measurement* 79 29
[48] Ng K C, Thu K, Kim Y, Chakraborty A and Amy G, 2013 *Desalination* 308 161