Experimental and numerical analysis of multi-disc heat exchanger efficiency in adsorption chillers powered with waste heat

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Abstract. The thermally-powered adsorption cooling systems capable to utilize industrial waste heat sources and environmentally friendly refrigerants are an effective way to decrease electricity demand due to cooling. The design of the heat exchanger combined with the sorption bed is crucial to enhance the heat transfer within the bed and in consequence, significantly contributes to the adsorption chiller efficiency. Therefore, the aim of the carried out research was to investigate the possibility of implementing the innovative multi-disc heat exchanger in an adsorption cooling technology. The logarithmic mean temperature difference, as well as temperature distribution within the investigated heat exchanger, were obtained with experimental and numerical research.

1. Environmental impact of adsorption cooling technology
The most important topics in research activities nowadays are energy and environment-related concerns. The European Union's interests are focused on the most effective method of reducing primary energy consumption because it directly contributes to the emissions of harmful substances into the atmosphere and air quality. An important element of activities aimed at increasing energetic efficiency is the maximum use of waste heat, solar power, cogeneration or exhaust gases from internal combustion engines and its conversion into usable energy [1].

The demand for cooling in the industrial and residential sectors has been increasing. The mechanical vapor-compression systems are used to meet such a demand for chill and their popularity results from high coefficients of performance (COP), small sizes and low weights. But they vastly contribute to global warming and ozone layer depletion due to the usage of harmful refrigerants [2]. Therefore, the development of an alternative solution to conventional cooling systems is a necessity.

The chillers based on adsorption cooling technology can be the perfect solution to the aforementioned issues [3]. They are capable to be powered with low-grade heat, which can be obtained from renewable sources, e.g. solar radiation [3], geothermal energy [4] or industrial waste heat [5] and they can be applied in combined cooling, heating and power (CCHP) systems in numerous industrial and commercial applications [6]. The adsorbates and adsorbents used in adsorption cooling technology are characterized by zero global warming potential and ozone depletion potential. Moreover, on the markets of the Middle and Far East, adsorption technology is intensively developed due to the possibility of desalination of seawater along with the production of cold.
2. Adsorption chillers

The adsorption is the binding of the adsorbate to the surface of the adsorbent. The adsorption cooling technology utilizes the physical sorption phenomenon, where the molecules of adsorbate are bound to the surface of the porous adsorbent by Van-der-Waals forces. These interactions are so weak that thermal vibrations even at low temperatures can break these bonds. Such behavior is used in the adsorption cooling during the regeneration of the sorption bed and allows shifting the process equilibrium towards desorption.

The adsorption is an exothermic and spontaneous process during which the entropy of the system decreases [4]. In contrast, the desorption is an endothermic process characterized by the production of heat. The combination of subsequent adsorption and desorption cycles is used to produce the cooling effect in the adsorption cooling technology.

The basic adsorption chiller consists of an evaporator, condenser, valves separating adjacent devices and at least one sorption bed as shown in Figure 1a. The bed is designed as a hermetic vessel with a built-in heat exchanger, which transfers heat between the sorbent and the heating/cooling medium (usually water). More than one sorption bed can be applied in order to assure continuous chill production. The granular packed adsorbent bed is usually used in the adsorption cooling systems [6] because it is characterized by high mass transfer performance due to the high permeability level.

![Figure 1. Single-bed, single-stage adsorption chiller: (a) design scheme; (b) Clapeyron diagram.](image)

The ideal adsorption refrigeration cycle is typically expressed by the Clapeyron diagram [7] with respect to isosteres of adsorbent-adsorbate pair as shown in Figure 1b. The sorption bed operates between the condenser pressure and the evaporator pressure as well as the minimum and maximum adsorbate concentration levels. The Clapeyron diagram (Figure 1b) illustrates the four ideal thermodynamic steps occurring in the bed i.e., isosteric preheating (A-B), isobaric desorption (B-C), isosteric precooling (C-D) and isobaric adsorption (D-A).

The literature reports valuable examples of research concerning the adsorption cooling technology and the potential for applying different heat transfer enhancements techniques. The replacement of the gaseous voids of low thermal conductivity between the individual grains of sorbent with the glue of better thermal properties was investigated in [8]. Aristov et al. [9] optimized the adsorption dynamics with the application of loose-grain sorbent. The insertion of metallic additives to the sorbent was investigated in [6,10]. The polydispersed composition of the sorption bed was analyzed by Girnik & Aristov [11] and Demir et al. [12]. Alam et al. [13] numerically investigated the heat exchanger design effect on the performance of closed cycle, two-bed adsorption cooling systems. The modifications of the heat exchanger design were also investigated in [14,14–16]. The finned tube heat exchanger was analyzed in [17] and flat-tube heat exchanger was examined in [18]. A 2D coupled heat and mass transfer model was used in [19]. Researches also evaluated adsorption pairs and silica gel/water has shown significant advantages in terms of thermal performance and environmental impact [6]. According to [20], the lowest temperature needed to regenerate the adsorption chiller bed is required for the silica gel-water pair.
Apart from experimental research, several numerical methods were applied in studies on adsorption cooling technology. Krzywanski et al. [21] successfully utilized genetic algorithms, neural networks and AI approach for adsorption chiller work cycle analysis. Papakokkinos et al. [22] presented a generalized three-dimensional CFD model based on unstructured meshes. A similar parametric study concerning finned tube heat exchanger was performed in [14]. Detailed analysis of flow characteristics and heat transfer within a packed bed of sorbent using CFD technique were also performed in [23,24].

Enhancing the adsorption kinetics by improving heat and mass transfer is necessary in order to improve the adsorption chiller performance [6], which depends on the design of a heat exchanger installed within the adsorption bed [25]. Therefore, the aim of the carried out research was to investigate the possibility of implementing the innovative multi-disc heat exchanger in an adsorption cooling technology.

3. The multi-disc heat exchanger

The innovative construction of a multi-disc heat exchanger combined with a sorption bed depicted in Figure 2 was investigated. The sorbent can be placed in separate disc-shaped packets, and the cooling/heating medium washes the packets of sorbent from the outside transferring heat. The prototype made of copper has been constructed in the lab-scale and the design allowed to deliver cooling/heating medium through the connecting pipes to the two separate and water-tight regions.

![Figure 2. 3D and cross-section views of the physical prototype of the multi-disc heat exchanger.](image)

4. Experimental research

The prototype of the multi-disc heat exchanger was experimentally tested as a water-water heat exchanger. Such approach allowed to eliminate the influence of sorption processes on the heat exchanger performance. Therefore, it was connected to the hot and cold water supplies as well as the measurement apparatus as depicted in Figure 3a.

![Figure 3. The multi-disc heat exchanger: a) experimental setup; b) temperature measuring points: A-F – hot water probes; 1-8 – cold water probes.](image)

The PT-100 temperature probes were installed in the selected discs as well as outside the discs in the water jacket of the heat exchanger as depicted in Figure 3b. The additional probes were installed in the inlets and outlets of both hot and cold water in order to determine the Logarithmic Mean Temperature Difference (LMTD). The LMTD was used to calculate the efficiency of heat transfer within the multi-disc heat exchanger.
5. Numerical research
The application of numerical simulation tools calibrated with experimental measurements is a practical and cost-effective approach for energy simulation and conjugate heat transfer analysis [23]. Therefore, the commercial CFD package, ANSYS Fluent 2019 R1, was applied to carry out the numerical research. The associative CAD model corresponding to the physical prototype of the multi-disc heat exchanger and consisting of three parts representing one solid and two fluid regions, was developed within the research. The model was parametrized and served as an input for the mesh generator. The computational domain discretization was carried out with the use of high-quality polyhedral elements and layered cells on the fluid wall boundaries. Mesh dependency studies incorporating the Grid Convergence Index (GCI) were carried out in order to estimate the numerical accuracy resulting from the mesh resolution. The GCI is recommended by the Fluids Engineering Division of the American Society of Mechanical Engineers to estimate the discretization error and was successfully applied in many research [26]. The discretization error calculated with the GCI method gained the value of 1.03%. The CFD solver was configured as pressure-based and the analysis was performed for steady-state. The standard k-ε viscous model was applied along with the enhanced wall treatment. Pressure-velocity coupling by the COUPLED algorithm was used as a solution method. Least squares cell-based spatial discretization was chosen in case of gradients, second-order in case of pressure, second-order upwind in case of momentum as well as energy and first-order upwind in case of turbulent dissipation rate. The model convergence was defined on the basis of qualitative and quantitative monitoring of residuals as well as the thermodynamic stability of the model. The applied boundary conditions correspond with the experimental research carried out in order to validate the multi-disc heat exchanger model. The heat transfer between fluid and solid subdomains was calculated as conjugate heat transfer.

6. Results
The temperature values registered with the PT-100 probes and calculated with the CFD code for cold water (probes 1-8) and hot water (probes A-F) are presented in Figure 4. The relative error between the numerical and experimental results concerning individual probes are shown in Figure 5.

![Figure 4. Measured and calculated temperatures: 1-8 – cold water probes, A-F – hot water probes.](image-url)

It can be noticed that the maximal error between experimental and numerical results concerning temperature in the selected points of the multi-disc heat exchanger does not exceed 7.0% (probe 5), which is 2.84°C. The mean relative error for the cold water temperature (probes 1-8) equals to 3.76% and for the hot water temperature (probes A-F) equals to 2.61%. The mean relative error for all the registered temperatures equals to 3.27%.

The efficiency of the heat exchanger was evaluated with LMTD. The LMTD value obtained for the experimental research was 27.19°C and for the numerical research, it was 1.35°C lower and equaled to 25.84°C. The LMTD relative error between the numerical and experimental results was 5.0%.
Figure 5. The relative error between the numerical and experimental research results: 1-8 – cold water probes, A F – hot water probes.

7. Conclusions
The computational fluid dynamics is an effective research tool for the design of adsorption cooling systems and the analysis adsorption chiller performance, which is directly dependent on the heat exchanger construction. The presented innovative multi-disc heat exchanger can contribute to the improvement of the design of adsorption packed bed reactors.

The proposed construction allows to place the device e.g. in the ceiling of the building or integrate it with solar panels, which will supply the device with the necessary heat. Such a solution allows to significantly expand the potential installation sites of the adsorption chillers. Another advantage of the proposed solution is its potential for scalability consisting of adjusting the number of sorbent discs to the expected cooling power of the device or the possibility of installing two or more multi-disc sorption beds with sorbent packages one above another with vapor ducts between them.

The analysis of the commercially available adsorption cooling equipment and the literature review showed that the presented solution is not the current state of the art. Therefore, a patent application was prepared for the Polish Patent Office on the basis of the presented multi-dish heat exchanger design.

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