The effect of heat exchanger geometry on adsorption chiller performance

Marcin Sosnowski¹, Karolina Grabowska¹, Jarosław Krzywański¹, Wojciech Nowak², Karol Szklerk² and Wojciech Kalawa²

¹Jan Długosz University in Częstochowa, ul. Waszyngtona 4/8, 42-200 Częstochowa, Poland
²AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Krakow, Poland

E-mail: m.sosnowski@ajd.czest.pl

Abstract. The adsorption technology applied to cooling production is one of the possible means of waste heat utilization and it therefore contributes to a reduction of power consumption in air-conditioning and desalination facilities. Increasing the performance of the adsorption chiller can be achieved by the intensification of heat transfer in the sorption bed which in turn is directly influenced by heat exchanger geometry. The carried out research utilized numerical methods to define the correlation between the fin-tube heat exchanger design and the main factors influencing adsorption chiller performance such as gradient of heating water temperature, logarithmic mean temperature difference, effective mass factor of silica gel, silica gel average temperature and spatial temperature distribution in the sorption bed. The obtained correlations can be used by sorption bed designers to balance the thermal effectiveness of the device and its overall dimensions and mass.

1. Introduction

The reduction of conventional energy consumption is the main assumption of the sustainable development concept for the global economy, therefore the utilization of low-temperature energy sources i.e. industrial waste heat, solar energy or cogeneration heat, is the intensively investigated area in power engineering. Air-conditioning facilities in highly developed countries, as well as desalination facilities in Middle-East countries are significant energy consumers therefore the reduction of their power consumption is crucial to the reduction of fossil fuel consumption.

The adsorption technology is one of the answers to the above mentioned challenge, as it allows cooling production, as well as desalinated water production, by utilizing low grade thermal energy sources. Moreover, it is an eco-friendly system as it does not use any environmentally hazardous refrigerants.

The adsorption chiller is composed of a sorption bed(s), evaporator and condenser while the first is the most important in terms of overall performance of the chiller. The sorption bed is equipped with a water-sorbent heat exchanger (HE). At least two beds should be used in order to assure continuous and effective operation of the chiller [1,2]. Cooling production with the use of adsorption process is based on periodic changes in temperature and pressure of the sorbent enclosed in said bed. The main factor influencing the performance of the adsorption chiller (described by coefficient of performance - COP) is the heat transfer between the heating/cooling water and the sorbent with the use of a HE [3]. Therefore,
the optimization of the chiller rated parameters depends on the intensification of heat and mass transfer in the sorbent bed. It is attainable by either modification of the sorbent composition in the bed [4,5], sorbent composition in the vicinity of the HE [6], or adjustment of the HE system design. The latter can be the application of fins characterized with various thickness and spacing [6].

2. Methods

The scope of the research is to analyze the influence of HE fins geometry on the intensification of heat transfer within the sorbent bed, keeping in mind the necessity of limiting the mass and dimensions of the device. Different approaches allowing describing the heat transfer process can be found in [7–10]. Since such analysis require many different configurations to be investigated and evaluated, Computational Fluid Dynamics (CFD) have been used as it allows achieving flawless product design at relatively low cost by combining the prediction of fluid flow, heat transfer and related phenomena [11–18].

The utilized CFD solver (ANSYS Fluent 19.0) employs an algorithm which belongs to a general class of methods called the projection method, where the constraint of mass conservation of the velocity field is achieved by solving a pressure equation. The pressure equation is derived from the continuity and momentum equations in such a way that the velocity field, corrected by pressure, satisfies the continuity. The solution process involves iterations in order to solve the nonlinear and coupled governing equations.

The solver was configured as pressure-based and the analyses were performed for a steady state. The 3D steady RANS equations were solved using standard the k–ε model with standard wall function and turbulence intensity of 5%. The choice of the turbulence model was made based on previous studies [19,20]. The model convergence was monitored and the iterations were terminated when all residuals decreased below 1 · 10⁻³.

2.1. The research object

The fin-tube HE of dimensions depicted in Figure 1 was the research object. It consisted of the cuboid filled with sorbent and the heat tube with fins of variable thickness and spacing. The parametrized CAD model with bi-directional associativity between the CAD geometry and numerical mesh generator was prepared as an assembly of three domains: sorbent, heat exchanger and water as depicted in Figure 2. Nine design configurations were built: different fin thicknesses (0.50 mm, 0.75 mm and 1.00 mm) and different fin spacing (2 mm, 3 mm and 4 mm). Moreover the model was prepared as periodic to allow the application of variable number of tubes and minimization of computational domain leading to CPU time reduction.

Figure 1. Dimensions of the HE (in mm) with variable thickness and spacing of fins.
2.2. Pre-processing and boundary conditions
The pre-processing was performed using ANSYS Meshing 19.0. Tetrahedral elements were used to
discretize the computational domain. Adaptive size function was employed and the element size
constrain was set to the value of 0.5 mm. Additional match control settings were applied in order to
generate a periodic mesh. The above mentioned meshing settings resulted in the final mesh consisting
of approximately four million elements. The mesh resolution was based on mesh sensitivity analysis
and generation guidelines described in [21]. The mesh quality was also taken into consideration. Such
analysis provides a matrix calculated on the basis of (1) that ranges between 0 and 1 (1 - perfect element,
0 - element of zero or negative volume). The element of the worst quality generated throughout the
entire research was characterized by the quality index of 0.17 and therefore it was assumed that the mesh
did not affect the numerical stability of the computational model.

\[ Q = C \cdot \frac{\nu}{\sqrt{\sum l^3}} \]  

where:
\( V \) – computational domain volume
\( C \) – constant characteristic for the applied mesh type
\( l \) – the edge length of the analyzed mesh element

The applied boundary conditions correspond with the desorption phase of the adsorption chiller work
cycle therefore heating water was the fluid medium. Mass-flow-inlet boundary condition was assigned
to the inlet of the heating water with mass flow rate equal 0.02 kg/s and temperature equal 343 K. The
outflow boundary condition was defined on the surface of water outflow. The heat transfer between the
corresponding subdomains was calculated as conjugate heat transfer. The desorption was modelled as
an endothermic process by applying source term of constant and negative value in the whole volume of
silica gel.

3. Results and Discussion
According to [22], the heating power of the adsorption chiller is directly proportional to the gradient of
heating water temperature (\( \Delta T \)) calculated as the difference of the temperature of the heating water at
the inlet and at the outlet of the HE. Therefore the obtained correlation between \( \Delta T \) and fin geometry
(spacing and thickness) is presented in Figure 3. It can be clearly seen that the temperature difference
and resulting heat transfer is proportional to the fin spacing and inversely proportional to fin
thickness.

Another important factor defining the influence of HE geometry on adsorption chiller performance
is the logarithmic mean temperature difference (LMTD) calculated according to formula (2). The
relation depicted in Figure 4 reveals the strong influence of fin spacing and thickness on LMTD,
which is crucial to adsorption chiller performance.

\[ LMTD = \frac{\Delta T_{inlet} - \Delta T_{outlet}}{\ln(\frac{\Delta T_{inlet}}{\Delta T_{outlet}})} \]  

where:
\( \Delta T_{inlet} \) – temperature difference between the heating water and the sorbent in the inlet
section of the bed [K]
\( \Delta T_{outlet} \) – temperature difference between the heating water and the sorbent in the outlet
section of the bed [K]

Designers of effective and simultaneously compact adsorption chillers strive to maximize the fraction
of silica gel mass in the overall mass of the device. Such dependency can be defined as the effective
mass factor (EMF) and it is calculated as the quotient of the silica gel mass to the mass of the device.
The carried out research showed that the maximization of the EMF requires minimizing the fin thickness
and simultaneously maximizing the spacing between them (Figure 5). Conversely, the average temperature of silica gel also directly influences the sorption kinetics and in consequence the performance of the adsorption chiller and it strongly depends on the geometry of the HE as depicted in Figure 6.

Figure 3. The correlation between heating water temperature gradient and HE geometry.

Figure 4. The correlation between logarithmic mean temperature difference and HE geometry.

Figure 5. The correlation between effective mass factor and HE geometry.

Figure 6. The correlation between silica gel average temperature and HE geometry.

Figure 7. Samples of temperature distribution in the vertical cross-section of the individual HE tube near the inlet obtained for fins spacing equal to 2 mm (a-c), 3 mm (d-f), 4 mm (g-i) and fins thickness equal to 0.50 mm (a, d, g), 0.75 mm (b, e, h) and 1.00 mm (c, f, i).

Figure 7 presents the samples of temperature distribution in the vertical cross-section of the HE near the heating water inlet, and Figure 8 depicts temperature distribution in the horizontal cross-section of the complete HE consisting of five tubes for nine analyzed cases characterized by different spacing and thicknesses of fins. Figure 6 to Figure 8 prove that the mean silica gel temperature decreases along with the increased fin spacing and decreased fin thickness.
4. Conclusions
The performed analysis allowed to identify the influence of fin spacing and thickness in the HE on the gradient of heating water temperature ($\Delta T$), logarithmic mean temperature difference (LMTD), effective mass factor (EMF) of silica gel, silica gel average temperature and spatial temperature distribution in the sorption bed. All the above mentioned factors directly influence the adsorption chiller performance but the requirement of acceptable mass & dimensions of the sorbent bed also has to be taken into consideration. Therefore the optimal balance between the thermal effectiveness of the device and its overall dimensions has to be individually selected in accordance with specific installation requirements.

The numerical analysis using CFD turned out to be an effective method of comprehensive heat transfer in sorption bed analysis but the applied sorption model has to be validated against experimental data and carefully parametrized in order to improve its reliability.

References
[1] Saha B, Koyama S, Lee J e al, Kuwahara K, Alam K, Hamamoto Y, Akisawa A and Kashiwagi T 2003 Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller International Journal of Multiphase Flow 29 1249–63
[2] Krzywanski J, Grabowska K, Herman F, Pyrka P, Sosnowski M, Prauzner T and Nowak W 2017 Optimization of a three-bed adsorption chiller by genetic algorithms and neural networks Energy Conversion and Management 153 313–22
[3] Khan M, Alam K, Saha B, Hamamoto Y, Akisawa A and Kashiwagi T 2006 Parametric study of a two-stage adsorption chiller using re-heat—The effect of overall thermal conductance and adsorbent mass on system performance International journal of thermal sciences 45 511–9
[4] Askalany A A, Henninger S K, Ghazy M and Saha B B 2017 Effect of improving thermal conductivity of the adsorbent on performance of adsorption cooling system Applied Thermal Engineering 110 695–702
[5] Grabowska K, Krzywanski J, Nowak W and Wesolowska M 2018 Construction of an innovative adsorbent bed configuration in the adsorption chiller-Selection criteria for effective sorbent-glue pair Energy 317–23

[6] Chang K-S, Chen M-T and Chung T-W 2005 Effects of the thickness and particle size of silica gel on the heat and mass transfer performance of a silica gel-coated bed for air-conditioning adsorption systems Applied Thermal Engineering 25 2330–40

[7] Blaszczyk A and Krzywanski J 2017 A comparison of fuzzy logic and cluster renewal approaches for heat transfer modeling in a 1296 t/h CFB boiler with low level of flue gas recirculation Archives of Thermodynamics 38 91–122

[8] Krzywanski J and Nowak W 2016 Modeling of bed-to-wall heat transfer coefficient in a large-scale CFBC by fuzzy logic approach International Journal of Heat and Mass Transfer 94 327–34

[9] Krzywanski J, Wesolowska M, Blaszczyk A, Majchrzak A, Komorowski M and Nowak W 2018 Fuzzy logic and bed-to-wall heat transfer in a large-scale CFBC International Journal of Numerical Methods for Heat & Fluid Flow 28 254–66

[10] Krzywanski J, Wesolowska M, Blaszczyk A, Majchrzak A, Komorowski M and Nowak W 2016 The non-iterative estimation of bed-to-wall heat transfer coefficient in a CFBC by fuzzy logic methods Procedia Engineering 157 66–71

[11] Jamrozik A, Tutak W, Gnatawski A, Gnatawski R, Winczek J and Sosnowski M 2017 Modeling of Thermal Cycle CI Engine with Multi-Stage Fuel Injection Advances in Science and Technology. Research Journal 11 179–86

[12] Sosnowski M 2017 Computer aided optimization of a nozzle in around-the-pump fire suppression foam proportioning system Engineering Mechanics 2017 914–7

[13] Sosnowski M, Krzywanski J and Gnatawski R 2017 Polyhedral meshing as an innovative approach to computational domain discretization of a cyclone in a fluidized bed CLC unit Energy and Fuels E3S Web of Conferences vol 14, ed Suwala, W. and Dudek, M. and Leszczyński, J. and Lopata, S.

[14] Gnatawski R, Sosnowski M and Uruba V 2017 CFD modelling and PIV experimental validation of flow fields in urban environments Energy and Fuels E3S Web of Conferences vol 14, ed Suwala, W. and Dudek, M. and Leszczyński, J. and Lopata, S.

[15] Gnatawski R and Sikora S 2015 Numerical analysis of wind flow and erosion in flow around the bump terrain AIP Conference Proceedings vol 1648 p 850124

[16] Gnatawski R and Rybak T 2015 Numerical analysis of heat transfer around 2D circular cylinder in pulsation inflow AIP Conference Proceedings vol 1648 p 850125

[17] Jaminska P, Blazik-Borowa E and Lipiecki T 2014 CFD study on wind action on buildings-scaffolding system Proc. 6th International Symposium on Computational Wind Engineering

[18] Jaminska P, Lipiecki T and Blazik-Borowa E 2014 CFD study and wind tunnel measurements of flow around prism Proc. 6th International Symposium on Computational Wind Engineering

[19] Sosnowski M, Krzywanski J, Grabowska K and Gnatawski R 2018 Polyhedral meshing in numerical analysis of conjugate heat transfer International Conference on Experimental Fluid Mechanics (EFM) 589–94

[20] Sosnowski M 2018 Computational domain discretization in numerical analysis of forced convective heat transfer within packed beds of granular materials Engineering Mechanics 2018 801–4

[21] Sosnowski M 2018 Computational domain discretization in numerical analysis of flow within granular materials International Conference on Experimental Fluid Mechanics (EFM) 582–8

[22] Krzywański J, Nowak W, Grabowska K, Widuch A and Wesolowska M 2017 Minimalizacja rozmiarów chłodziarek adsorpcyjnych wykorzystywanych do produkcji wody lodowej Część I. Chłodziarki adsorpcyjne - charakterystyka Energetyka Cieplna i Zawodowa 56–64