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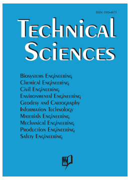

FUZZY LOGIC APPROACH IN THE ANALYSIS OF HEAT TRANSFER IN A POROUS SORBENT BED OF THE ADSORPTION CHILLER

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Abstract

Thermal conductivity in the boundary layer of heat exchange surface is the crucial parameter of adsorption process efficiency which occurs in the adsorption bed. In order to improve heat transfer conditions in the adsorption chiller, novel constructions of adsorption beds are currently investigated. The porous structure of the sorbent layer causes low thermal conductivity in the adsorption bed. One of the methods to improve heat transfer conditions is a modification of porous media bed structure with glue which is characterized with higher thermal conductivity. The optimum parameters of sorbents and glues to build the novel coated construction, in terms of improving the chiller Coefficient of Performance (COP) were defined in (Grabowska et al. 2018a). The paper implements fuzzy logic approach for predicting thermal conductivity of modified porous media layers. The developed model allows determination of the sorbent layer thermal conductivity based on various input parameters: arithmetic average of particle distribution d, density ρ and thermal diffusivity k. The data from empirical research was used to build up the model by fuzzy logic methods.

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Nomenclature

C_p – specific heat capacity, J/(kg·K)
COP – coefficient of performance
Q_e – heat received in the evaporation process, J
Q_h – heat supplied during preheating phase of adsorption bed, J
Q_d – heat supplied during desorption phase of adsorption bed, J
d – arithmetic average of particle distribution, the averaged distance between the particles centers, m
k – thermal diffusivity of coated sorbent sample, m^2/s
λ – thermal conductivity, W/(m·K)
ρ – density of coated sorbent sample, kg/m^3
M – metal mass of heat exchange surface, kg
m – adsorbent mass in adsorption bed, kg

Introduction

Adsorption refrigeration technology is an alternative source of cooling which significantly reduces electrical energy consumption for purposes of air conditioning. This technology utilizes low grade thermal energy sources as power supply for the adsorption chiller. Therefore, this technology will be a promising concept for sustainable development of the global economy. In the papers (SZTEKLER et al. 2017, KRZYWANSKI et al. 2018a) adsorption chillers driven by waste heat were investigated, and the possibility of utilizing heat produced in cogeneration was proven in (CHOROWSKI, PYRKA 2015). The biggest barrier in popularizing this ecological technology is the significantly lower coefficient of performance (COP) as compared with conventional refrigeration systems. This parameter of chiller efficiency is described by equation:

$$\mathrm{COP} = \frac{Q_e}{Q_h + Q_d} \tag{1}$$

Therefore, research for the improvement of working cycle efficiency is being conducted. The crucial area of research is the heat transfer condition in the vicinity of the heat exchanger surface where this process is strongly limited by the porosity of the sorbent layer and the low thermal conductivity of the adsorption bed. Multiple factors are examined to improve the heat transfer processes, for example, a polydispersive structure of the sorbent bed, finned heat exchangers and changes to the working cycle conditions. The influence of metal additives on thermal resistance decrease in adsorption beds was also observed experimentally in (SHARAFIAN et al. 2014, ASKALANY et al. 2017). The optimization of fins geometry and metal mass/adsorbent mass (M/m) ratio were conducted in (FRENI et al. 2007, ROGALA 2017).

Experimental research of adsorbent bed thermal conductivity were conducted in (ROUHANI et al. 2018, ZHU, WANG 2002). The researchers have examined thermal properties of different types of porous media which are used in fixed adsorption beds. An analytical model and experimental studies of heat transfer in fixed bed of composite sorbent were presented in (FERREIRA et al. 2002). The well-known experimental research is supplemented by numerical models using Computational Fluid Dynamics (CFD) methods or artificial intelligence approach. It allows reduction of experiments costs because CFD methods enable study of a working cycle of an adsorption chiller numerically without expensive measurements and research stands. The CFD model of an adsorption bed, which was built based on boundary conditions from experimental thermal conductivity measurements of the sorbent layers is presented in (GRABOWSKA et al. 2018b). The special nature of heat and mass flow within porous media layers require formulating a specific computational domain in order to correctly describe the actual process. The novel approach to prepare the numerical simulations, especially in porous media volume, were discussed in (SOSNOWSKI 2017). Numerical modelling was used to optimize the performance of the silica gel/water multi-bed adsorption chiller in (REZK et al. 2013). Different mass allocation in the beds and various cold water temperatures were analysed. Improvement of cooling capacity by 10.78% was observed when cold water temperature was maintained at 20°C.

Artificial intelligence (AI) algorithms are another innovative method for adsorption chiller optimization. Neural networks and genetic algorithms were used to improve the cooling capacity (CC) of a three-bed adsorption chiller in (KRZYWANSKI et al. 2017). Calculated accuracy was excellent and the measured data has been preserved. The maximum relative error is lower than 10%. The AI modelling of a re-heat two-stage adsorption chiller was also presented in (KRZYWANSKI et al. 2018). In the paper (KRZYWANSKI, NOWAK 2016a) an alternative AI method was used to calculate the heat transfer coefficient in the combustion chamber of a circulating fluidized bed combustor (CFBC), which constitutes the fuzzy logic (FL) approach. Based on a specific set of received input data, the value of heat transfer coefficient at the output were determined. This modelling method also allows assessment of the individual input data impact on the output parameter. The most popular systems which use the fuzzy logic algorithms are consumer electronics based on fuzzy controller applications and also industrial and engineering automation systems. Moreover, new areas of FL applications are currently being researched (SOBOLEWSKI et al. 2016, HE et al. 2016).

The aim of this paper is to use the fuzzy logic approach in the analysis of heat transfer in a porous sorbent bed of an adsorption chiller.

Methods

The fuzzy logic model of thermal conductivity was built based on experimental measurements performed using the LFA (Laser Flash Methods) MicroFlash apparatus for different coated sorbent samples. Silica gel of various granulation was used as a sorbent and two different epoxy resins were used as a glue material. In the paper (GRABOWSKA et al. 2018a) it was proved that epoxy resin meets the conditions as the material to fill gaseous spaces in the adsorbent bed. The sample geometry used in the experiments is shown in Figure 1. Silica gel was used in the granulation range from $7 \cdot 10^{-4}$ to $10 \cdot 10^{-4}$ [m]. The particles distribution d means the averaged distance between the particles centers and this parameter was given by manufacturer of the silica gel. The results of experimental tests are presented in Table 1.

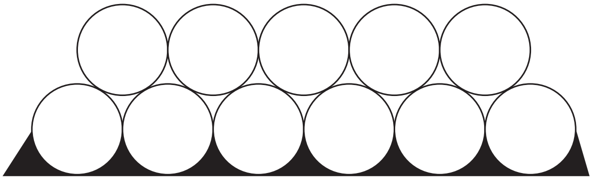


Fig. 1. Coated porous media sample geometry

Table 1

Results of thermal conductivity of experimental tests

d [m]	ρ [kg/m^3]	k [m^2/s]	λ [W/mK]
$7.5 \cdot 10^{-4}$	651	$4.05 \cdot 10^{-7}$	0.504
$7.5 \cdot 10^{-4}$	691	$3.21 \cdot 10^{-7}$	0.530
$8.5 \cdot 10^{-4}$	667	$2.95 \cdot 10^{-7}$	0.429
$8.5 \cdot 10^{-4}$	682	$3.03 \cdot 10^{-7}$	0.488
$9.0 \cdot 10^{-4}$	452	$2.49 \cdot 10^{-7}$	0.350
$9.0 \cdot 10^{-4}$	561	$2.07 \cdot 10^{-7}$	0.323

Fuzzy Logic modelling constitutes one of the calculation algorithms of the artificial intelligence. This model uses attribution operation of linguistic variables to fuzzy sets in order to qualitative evaluation of the considered process. To perform the model, input parameters should be covered by the fuzzy sets F, where numeric value of parameter corresponds to membership degree from the range of [0,1], which can be expressed by the Zadeh's notation (KRZYWANSKI et al. 2018b):

$$F = \left\{ \frac{\mu_F(i_1)}{i_1} + \frac{\mu_F(i_2)}{i_2} + \cdots + \frac{\mu_F(i_n)}{i_n} \right\} \tag{2}$$

where:

i_1, i_2, i_n are input parameters and μ_F degree of membership to fuzzy set.

The main parts of a FL model are the fuzzifier, fuzzy rule base, the inference engine and defuzzifier. Further detailed information about the algorithms implemented in QtFuzzyLite software can be found in (KRZYWANSKI et al. 2018b, 2016b, BŁASZCZUK, KRZYWANSKI 2017).

In this case, the arithmetic average of particle distribution d, density ρ of coated sample, their thermal diffusivity k constitute input parameters to which linguistic terms were assigned. The selection of input parameters is related to the used thermal conductivity measurement method. LFM MicroFlash apparatus directly measures the thermal diffusivity of porous media. Thermal conductivity is calculated based on the relationship (FODEMSKI 2001):

$$k = \frac{\lambda}{\rho \cdot c_p} \quad [\mathrm{m^2/s}] \tag{3}$$

The output parameter is the analysed thermal conductivity of a coated sorbent layer. The FL model was built in QtFuzzyLite™ 6 software. Based on experimental results, the fuzzy rule base was prepared according to Table 2. This base describes the influence of each parameter on the value of a coated sorbent layer's thermal conductivity. The detailed description of the methodology can be found in (KRZYWANSKI, NOWAK 2016).

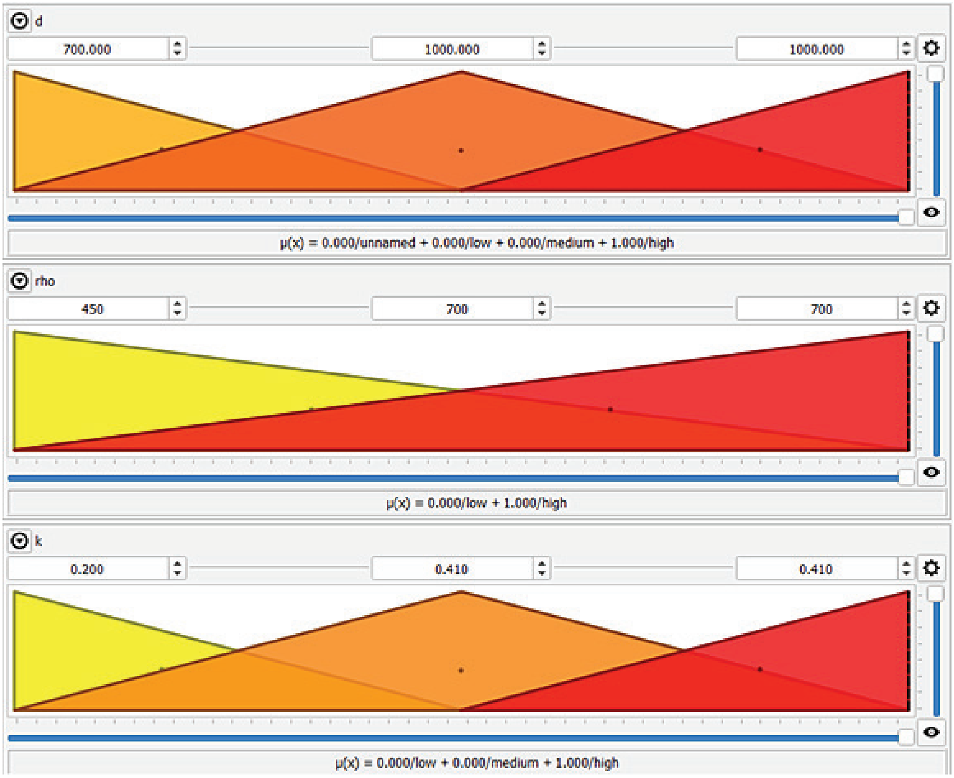
Table 2

Fuzzy rule base: *L* – low, *M* – medium, *H* – high

λ [W/mK]	*L*	*M*	*H*
d [µm]	*H*	*M*	*L*
ρ [kg/m^3]	*L*	*H*	*H*
k [mm^2/s]	*L*	*H*	*H*

Results and discussion

The input data are assigned to three overlapping triangle linguistic variables of low (*L*), medium (*M*), high (*H*). The same linguistic variables were used to depict values of thermal conductivity λ at the output. The membership of each variable to fuzzy sets for the input data is shown in Figure 2. The triangular functions were employed as they are the simplest and most widely used.



d

700.000 1000.000 1000.000

μ(x) = 0.000/unnamed + 0.000/low + 0.000/medium + 1.000/high

rho

450 700 700

μ(x) = 0.000/low + 1.000/high

k

0.200 0.410 0.410

μ(x) = 0.000/low + 0.000/medium + 1.000/high

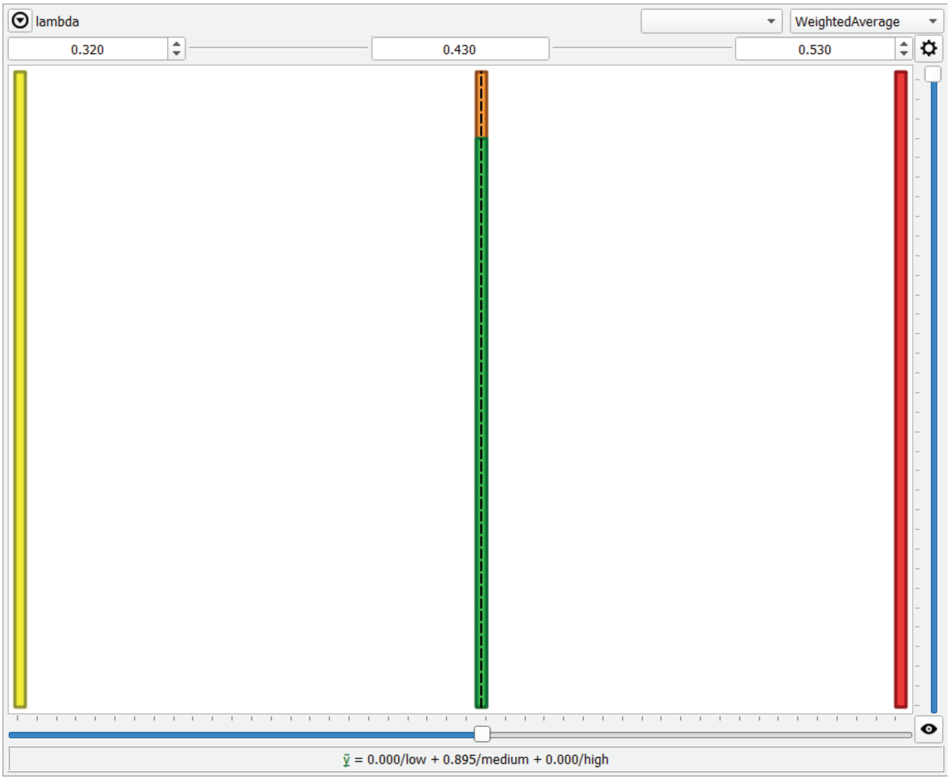
Fig. 2. Input data block with linguistic terms, where d is the arithmetic average of particle distribution, ρ is density of coated sample and k is their thermal diffusivity

The same approach was used in (DRAGOJLOVIC et al. 2001, KUCUKALI, BARIS 2010, KRZYWANSKI, NOWAK, 2016a). The membership of output parameter is given in Figure 3.

The comparison of obtained measured and model values of thermal conductivity is presented in Figure 4. In Table 3, the obtained results have been supplemented by the approximation error. The maximum relative errors are located within the range of ±5% with reference to the measured data. As shown, the developed fuzzy logic model has very good consistency with the experimental measurements.

The developed model was applied to predict thermal conductivity depending on the granulation and thermal diffusivity of a sorbent layer. The results of modelling are shown in Figure 5.

The calculations confirm that the thermal conductivity of the porous media layer strongly depends on arithmetic average of particle distribution. The sorbent layer with smaller granulation is characterized by much smaller amounts of gaseous spaces which significantly improves conductivity



0.320 0.430 0.530

ỹ = 0.000/low + 0.895/medium + 0.000/high

Fig. 3. Output data block with linguistic terms, where lambda is the thermal conductivity of a coated sorbent layer

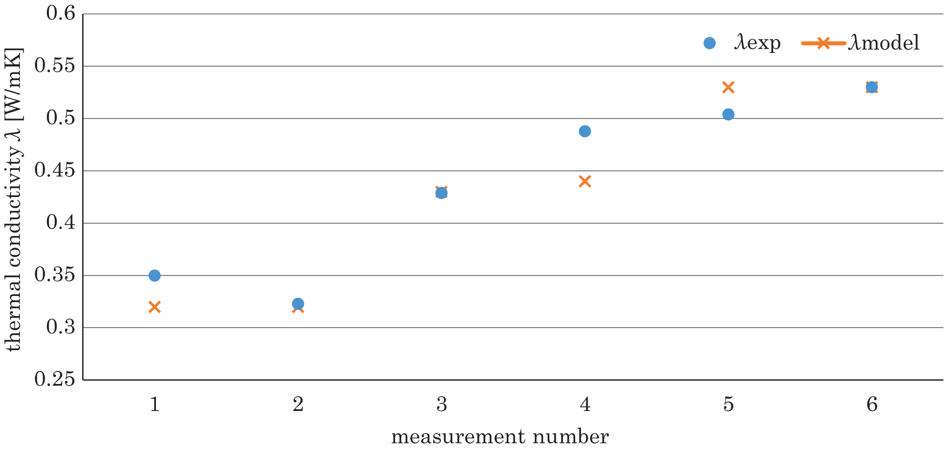


Fig. 4. Comparison of obtained measured and model values of thermal conductivity

Table 3.

Results calculated by the FL model with marked of maximum error

No	$\lambda_{experimental}$ [W/mK]	λ_{model} [W/mK]	Error [%]
1	0.35	0.32	3
2	0.323	0.32	0.3
3	0.429	0.43	0.1
4	0.488	0.44	4.8
5	0.504	0.53	2.6
6	0.53	0.53	0

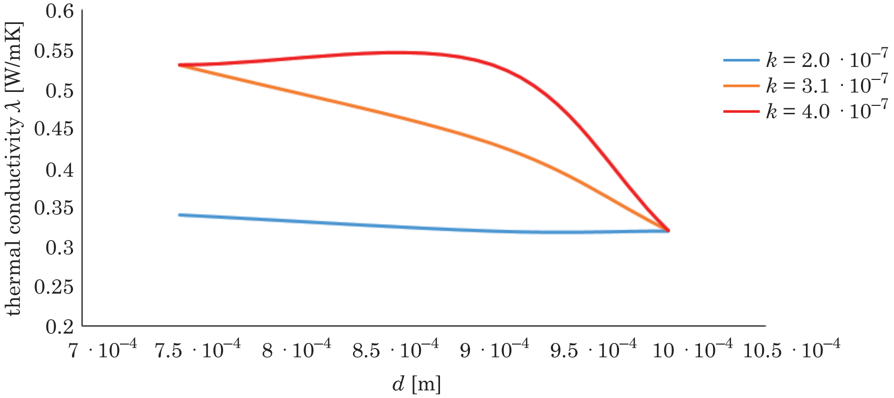


Fig. 5. Predicted values of thermal conductivity in function of *d* [m] for different amount of *k* [m^2/s]; $\rho = 560$ [kg/m^3]

of the considered bed layer. One of the methods of heat transfer intensification is the use of a glue layer which increases thermal diffusivity of the porous media layer. This solution is applied in the coated construction of adsorption beds.

Conclusions

The aim of this paper was to introduce the fuzzy logic methods to the analysis of heat transfer in a coated layer of porous media. The FL model was built to calculate the values of thermal conductivity. The differences in the obtained results were lower than ±5%. Therefore, the model's compatibility with measured data is very good. The fuzzy logic method can be very useful in the prediction of sorbent layer thermal parameters and optimization of working conditions for an adsorption bed. The developed model allows optimization of adsorption bed configuration leading to increased thermal conductivity of the considered adsorption bed. However, in this case, the number of measurements is too low to extrapolate the model to a wider range of porous media thermal conductivity.

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