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Application of a statistical design for analyzing basic performance characteristics of the cross-flow Maisotsenko cycle heat exchanger

Demis Pandelidis *, Sergey Anisimov

Department of Environmental Engineering, Wroclaw University of Technology, 27 Wyspiański St., 50-370 Wroclaw, Poland

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A B S T R A C T

This paper presents the simplified model generated by response surface methodology (RSM) for analyzing basic performance characteristics of the Maisotsenko cycle heat and mass exchanger. A five-level central composite design (CCD) was employed and filled with the experimental data and data obtained from the validated numerical model. Four performance factors were selected as the representative responses: outlet product airflow temperature, specific cooling capacity, dew point effectiveness and the theoretical COP. The statistical significance, accuracy and overall predictive capability of the model developed was examined using *F*-test, regression analysis of the coefficient of determination R^2 and absolute average deviation (AAD) by comparing predicted responses with the experimental data. The statistical approach identified the effect of five independent parameters on the selected performance characteristics and the effectiveness of heat and mass transfer processes in the channels of the cross-flow M-cycle exchanger was found to be significantly influenced by supply airflow mass flow rate, inlet air temperature and relative humidity. The models developed allow for the fast and precise calculation of the most important performance factors of the Maisotsenko cycle heat and mass exchangers in a variety of climate conditions. The results of this study have clearly demonstrated high efficiency of the examined heat exchanger and possible ways of its improving.

1. Introduction

The rising living standards lead to the high air-conditioning demand, especially in summer time in high temperature areas. This high demand results in an increased electricity consumption, due to the fact that the most popular cooling devices are based on mechanical compression systems [1–3]. It becomes necessary to develop new sources of cooling power, which could be less dependent on the electric energy. The use of indirect evaporative cooling as a new source of cooling energy looks very promising, both in the field of electricity consumption and in the direction of abandoning dangerous refrigerants, since its working medium is water. Currently new methods of evaporative air cooling, called sub-wet bulb evaporative cooling, have been developed and they are able to achieve very low outlet air temperatures (theoretically, the limit for these cycles is the ambient air dew point temperature [4]). Sub-wet bulb evaporative cooling is then a new innovative way to produce cooled air for air conditioning systems without adding humidity to the supply airflow and using dangerous refrigerants. One of the most promising methods of achieving a low temperature level of the air-conditioning air is the novel cycle, known as the M-cycle (Maisotsenko cycle) [1–7]. This unique technique was investigated by many authors. Balyani et al. [5] presented the analysis of the best cooling strategy based on thermal comfort and 3E (energy, economic and environmental) analyses for small scale residential buildings at diverse climatic conditions. It was established that in temperate and humid, very hot and semi-humid, and temperate and wet cities, desiccant-enhanced evaporative cooling was the best solution. Gao et al. [6] experimentally analyzed an integrated liquid-desiccant indirect evaporative air-cooling system with the M-cycle. The results showed that the dehumidification process in the first stage of the cycle has direct impact on the cooling capacity in the second stage. Caliskan et al. [7] presented energy and exergy analysis of one of the most effective indirect evaporative air cooling cycles: the Maisotsenko cycle. The results indicated that maximum exergy efficiency is found to be 19.1% for a reference temperature of 23.9 °C where the optimum operation conditions take place. Cui et al. [8] analyzed numerically the novel M-cycle heat and mass exchanger (HMX) based on a counter-flow closed-loop configuration consisting of separated working channels and product channels. Simulation results have indicated that the novel dew point evaporative air conditioner is able to achieve a higher wet-bulb and dew point effectiveness with lower airflow velocity, smaller

* Corresponding author.
E-mail address: demis.pandelidis@pwr.wroc.pl (D. Pandelidis).

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Nomenclature

c_p	specific heat capacity of moist air [J/(kg K)]
COP	theoretical energy efficiency factor of the system, COP = Q_1/N [–]
f	fluid fraction coefficient [–]
h	height of the heat exchanger channel [m]
G	moist air mass flow rate [kg/s]
L_X	supply air streamwise length of the cooler [m]
L_Y	working air streamwise length in the wet channel of the cooler [m]
L_Y^{work}	channel width of the dry working part of the heat exchanger, representing the size of the initial part of the exchanger [m]
N	theoretical fan power [W]
Q_1	cooling capacity rate [W]
$\hat{Q}$	specific cooling capacity per cubic meter of the heat exchanger's structure, $\hat{Q} = Q_1/V_{HMX}$ [kW/m^3]
RH	relative humidity [%]
t	temperature [°C]
$\bar{t}$	average temperature [°C]
V_{HMX}	volume of the HMX structure $V_{HMX} = 2(h + \delta_{plt})\ L_X\ L_Y$ [m^3]
W	heat capacity rate of the fluid [W/K]
X	coordinate along the supply airflow direction [m]
Y	coordinate perpendicular to X coordinate [m]
Δp	pressure drop [Pa]

Special characters

α	convective heat transfer coefficient [W/(m^2 K)]
ε_{DP}	dew point effectiveness, $\varepsilon_{DP} = (t_{1i} - \bar{t}_{1o})/(t_{1i} - t_{1i}^{DP})$ [–]

Non dimensional coordinates

$\bar{l}_Y^{work}$	relative channel width of the dry working part of the heat exchanger, $\bar{l}_Y^{work} = L_Y^{work}/L_Y$ [–]
NTU	number of transfer units, NTU = $\alpha F/(Gc_p)$ [–]
Re	Reynolds number [–]
k	the number of factors ($k = 5$) [–]
n^*	the number of experimental runs in the factorial portion of the design ($n^* = 2^k = 32$) [–]
n_r	the number of repetitions of experiments at the centre point of the design ($n_r = 8$) [–]
n_α	the number of axial points in the design ($n_\alpha = 2k = 10$) [–]
n	the number of experimental runs ($n = n^* + n_r + n_\alpha = 50$) [–]
X_i, X_j	coded independent variables [–]

Subscripts

1	product (supply) air flow
2	working air flow in the wet channels (product part of exchanger)
DP	dew point
i	inlet
o	outlet
product	referenced to the product part of the heat exchange
work	referenced to the working part of the heat exchange
X	air streamwise in the dry channels
Y	air streamwise in the wet channels

channel height, larger length-to-height ratio, and lower product-to-working airflow ratio. It is clearly visible that researchers showed a high potential of the Maisotsenko cycle to become the environmentally friendly and cheap source of energy for cooling. Currently, the most popular exchanger which utilizes the Maisotsenko cycle is the cross-flow heat and mass exchanger [1,2,4,9]. This device with unique design (Fig. 1) is claimed to be the most effective compromise between cooling effectiveness, low production costs and easy application potential [9].

Many authors investigated the cross-flow Maisotsenko cycle HMX numerically [1–4,10–18]. Reviews presented in our previous studies [2,4,10,12,18] showed that numerical models describing heat and mass transfer process in the Maisotsenko cycle cross-flow heat exchanger are rather complex and cumbersome for everyday use. Moreover, numerical models based on partial differential and algebraic equations require substantial computational time. Therefore, it is essential to develop a practical, accurate and fast mathematical method to calculate the performance of the M-cycle HMXes which may by applicable for engineers. Such method may also be used for optimization of the M-cycle exchangers, because it can significantly reduce a time of calculations. The

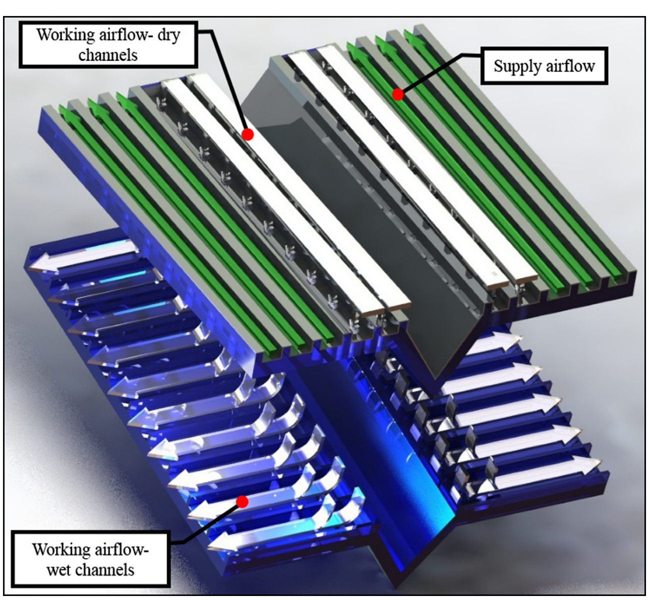

Fig. 1. Cross-flow Maisotsenko cycle HMX.

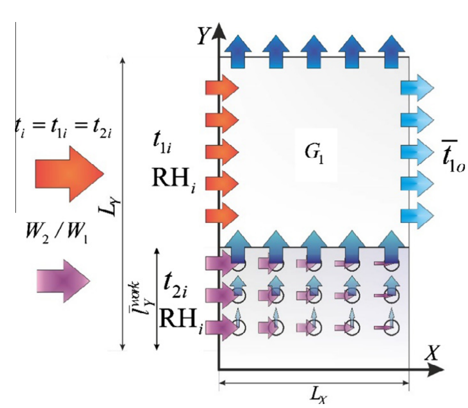

Fig. 2. Independent variables chosen for the modeling purpose.