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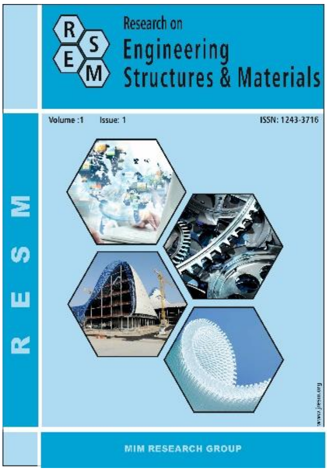

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Research Article

Numerical investigation of a heat wheel performance used for enthalpy recovery applications

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Abstract

Heat wheel is a heat exchanger in which the working fluid is air and it has parallel and counter current flow layout. These type heat exchangers are used for enthalpy recovery and/or air dehumidification processes. By means of numerous micro channels they have, it is enable for the heat wheels to transfer the heat so quickly and in a short span of time, which makes them superior. In this paper, performance of the heat wheel used for enthalpy recovery has been numerically determined. Utilizing Computational Fluid Dynamics (CFD) algorithm, the alteration of the wheel efficiency with time has been investigated for optimum rotation speed. With the help of ANSYS Fluent™ software in which calculations have been made, the temperature distributions by location have been presented graphically. Consequently, it is found that maximum efficiency of the heat wheel is 52.62 %.

1. Introduction

Heat exchangers are widely used for many processes ranging from HVAC to cooling applications [1]. One of the most commonly used heat exchanger in the air conditioning systems is heat wheel, i.e. desiccant wheel. A heat wheel consists of a number of micro channels in which heat and / or mass transfer occur. The main materials that provide the heat wheel to be efficient are hygroscopic (adsorbent) materials like lithium chloride (LiCl), silica gel and so on. These materials are impregnated a paper and then the whole micro channels are coated by this adsorbent-impregnated paper [1]. Because of the porous medium the adsorbents have, heat and/or moisture are adsorbed in the surfaces of the micro channels.

The heat wheels operate by rotating between two air streams (Fig. 1). While the former air stream is humid and hot, the latter one is vice versa. These air streams are generally called as process air and exhaust air, in turn. Furthermore, the compactness (β), the ratio of the heat transfer area to the heat exchanger volume, is so high (between 1600-16000 m2/m3) for this type heat exchangers [2]. The reasons mentioned above are the indicators why the heat/mass transfer in the heat wheels is realized quickly and efficiently. There are lots of studies in literature on this subject. For instance; Nobrega and Brum (2008) have composed a basic mathematical model for rotating regenerative heat-mass exchangers [3]; Tu et al.(2013) have developed a mathematical model for a heat wheel they have designed used for enthalpy recovery and air dehumidification and then they have validated this mathematical model [4]; Lee and Kim (2014) have developed an integral model for the desiccant wheels [5]; Ruivo et al. (2011) numerically investigated the influences of the

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atmospheric pressure on the heat and mass transfer rate [6]; Niu and Zhang (2002) simulated the heat and mass transfer in a desiccant wheel in which solid material resistance is 2-dimensional, axial and radial [7]; Zhang et al. (2014) investigated the efficiency of a honeycomb type adsorbent bed by using different hygroscopic materials and determined the effect of hygroscopic material on the performance [8]; Enteria et al. (2010) made experiments to determine the performance of heat and desiccant wheel by using them with and without together and then calculated the coefficient of performance of the system [9] and finally Sphaier and Worek (2006) formed a mathematical model assuming heat and mass transfer realized at 2-D in order to view the axial diffusion in desiccant wheels [10]. That said, the number of both experimental and numerical studies regarding desiccant wheels are not undeniable [11-19].

It is also seen from the literature review that performance analysis for these type heat exchangers was conducted under the some assumptions like presuming the heat transfer is time-independent and one-dimensional. Furthermore, the effect of the rotation on the thermal performance of the heat wheel was investigated in a few studies. Therefore, the heat transfer realized in a heat wheel was determined via CFD approach for three-dimensional, steady and unsteady conditions. A novel solid model was created and analysed numerically. The efficiency of the heat wheel that is of sinusoidal fins were numerically determined for the optimal rotation speed of 10 rpm. The results were given both stationary (N=0 rpm) and rotating (N=10 rpm) conditions of the heat wheel.

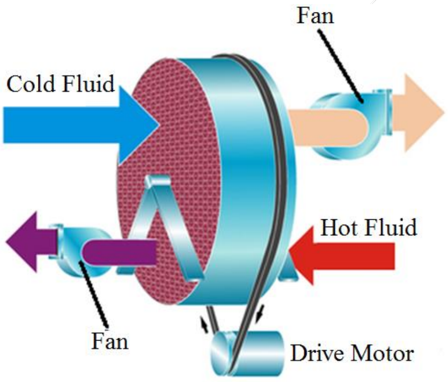

Fig. 1. Schematic view of the heat wheel

2. Material & Method

In this study, the numerical investigation of the performance of the heat wheel used the silica gel as the adsorbent material is carried out. The heat wheel analysed numerically is of 1 m length and 300 mm diameter, but only an annulus-shaped micro channel has been analysed because of the fact that all channels are the same (Fig.2).

Annulus-type heat wheel geometry has 100 mm length, 17 mm inner and 22 mm outer diameter. The wall thicknesses of both the fins and the base material are 2.5 mm. This geometry has been composed using a CAD software.

The obtained model then has been transferred into the ANSYS Fluent™ software. After the control of the created model, the mesh structure has been comprised into the Meshing part. The sweep and curvature method have been chosen due to the geometry shape and their superiority over the other (proximity, tetrahedrons and so on) meshing methods. Some information about the meshing is given in Table 1.

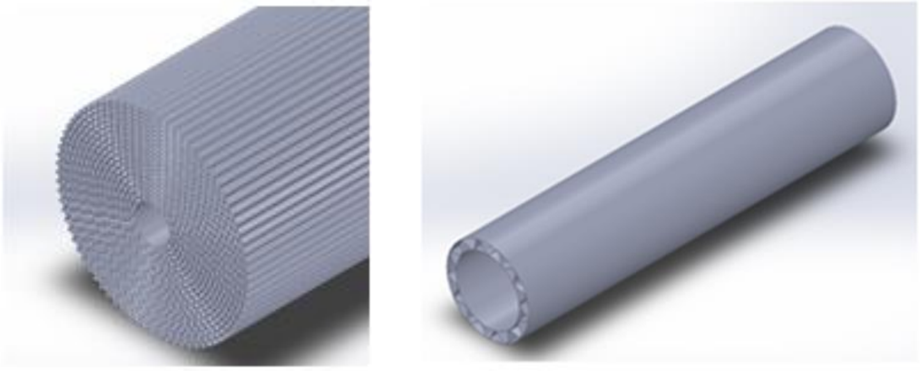

Fig. 2. A general view of the heat wheel modelled and used in analyses

The pressure-based solver in the transient mode is utilized to analyse the heat wheel performance in ANSYS Fluent™. Gravity also has been taken into account while calculating the solution for the sake of natural convection. In order to describe the rotation of the heat wheel, Sliding Mesh Method (SMM) which is a sub-method in the Dynamic Mesh Method (DMM) has been put account by activating the mesh motion in the Cell Zone Conditions menu.

Table 1. Meshing properties of the model

Properties	**Value**
Elements (pieces)	508794
Nodes (pieces)	542340
Orthogonal quality (-)	0.86
Skewness (-)	0.29
Element Quality (-)	0.82

In the CFD based numerical analyses, some data called as residual for every grid are come about because of the fact that governing equations' term cannot be compiled at only one side of the equation. The sum of these data never be zero, but proximity to zero of them have an idea whether solution is true or not, which process is called as convergence. In CFD solutions, convergence criteria are determined before the calculations and convergence of the solution to this criterion is observed. The convergence criteria for this study is identified as 10^{-6} and the solutions are converged about 240 iterations (Fig. 3).

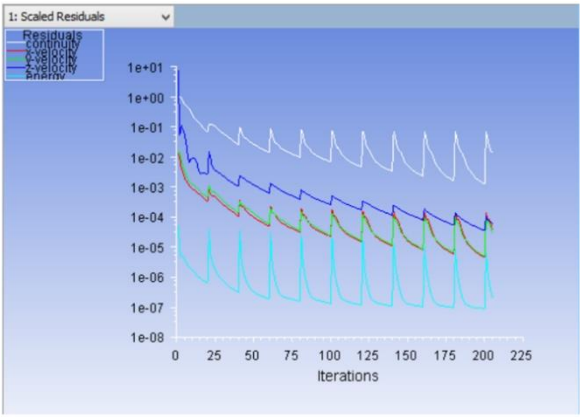

Fig 3. Convergence graph of the governing equations

3. Results and Discussions

The effectiveness (ε) for the heat exchangers are expressed as the ratio of transferred heat quantity (Q) to the maximum heat transfer could happen (Q_{max}). For both fluids are the air, this equation can be stated as shown Eq. (1).

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{T_{2,o} - T_{2.i}}{T_{1,i} - T_{2,i}} \tag{1}$$

where 1 and 2 indices represent the process (hot) air and exhaust (cold) air; i and o, in addition, stand for the inlet and outlet, respectively.

Performance analysis of the heat wheel has been conducted using the rate aforementioned. The outlet temperatures of both air streams have been obtained from the numerical analysis. These values can be seen in Table 2. The initial conditions, that is inlet temperatures (K) and velocity (m/s) values for the two air streams, are also depicted in Table 2.

Table 2. Temperature and velocity values of the two air streams

	N= 0 rpm (steady-state mode)	**N= 10 rpm (transient mode)**
$T_{1,i}$ (K)	308.15	308.15
$T_{2,i}$ (K)	297.15	297.15
$T_{1,o}$ (K)	304.35827	302.93826
$T_{2,o}$ (K)	300.71633	302.71823
air-inlet-velocity of process air(m/s)	3.8	
air-inlet-velocity of exhaust air (m/s)	3.8	

Using the Eq. (1), the maximum effectiveness of the heat wheel rotating at N=10 rpm is found 0.5262. (Eq. (2)) It means that when the heat wheel operates at N=10 rpm rotational speed, it provides enthalpy (heat) recovery up to 52.62 %. As a result of this, it is easily said that the energy requirements of the whole system are reduced at the same ratio.

$$\varepsilon = \frac{T_{2,o} - T_{2.i}}{T_{1,i} - T_{2,i}} = \frac{302.93826 - 297.15}{308.15 - 297.15} = \frac{5.78826}{11} = 0.5262 \tag{2}$$

In order to show the effect of rotation, an analysis has been realized at the N=0 rpm rotational speed, namely steady state or stationary conditions. The findings obtained from this analysis are given in Fig. 4. Applying the Eq. (1) for this analysis;

$$\varepsilon = \frac{T_{2,o} - T_{2.i}}{T_{1,i} - T_{2,i}} = \frac{300.71633 - 297.15}{308.15 - 297.15} = \frac{3.56633}{11} = 0.3242 \tag{3}$$

effectiveness is found 0.3242. The temperature differences during the rotating and stationary conditions are graphically demonstrated for different locations in Fig. 4. As can be seen from this figure that, the heat transfer is taken place more actively towards outwards of the channel than that of the inwards. This is because the both air streams inside the wheel are influenced by centrifugal forces.

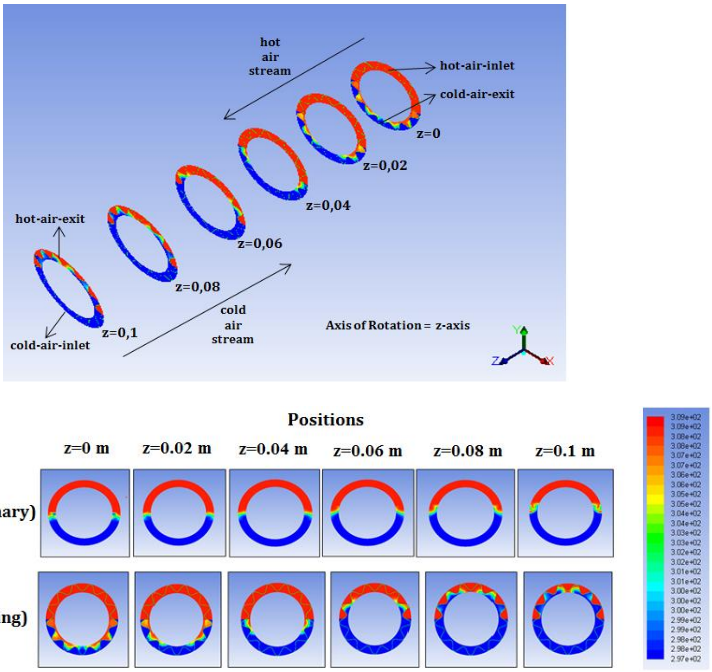

Fig. 4. The temperature differences under rotating and stationary conditions

Table 3. Some thermophysical properties of silica gel

Properties	Value
Type	A
Porosity (Å)	0.7
Thermal conductivity (W/mK)	0.174
Density (kg/m^3)	730
Specific heat capacity (j/kgK)	921

The thermophysical properties of silica gel (Table 3) also affect the heat transfer form. Furthermore, using the adsorbent material, it is enabled to transfer the heat not solely in a short span of time, but also more efficient than ever before.

3.1. Mesh Independence

The results obtained from the CFD analyses must be independent from the mesh structure. That is, the results gained from different mesh structures must be the same or include an acceptable error. To show off mesh independence, three different meshes are formed and then the analyses are conducted for 10 rpm rotational speed, separately. The mesh independence of the solution is established by comparing the analyse outcomes for outlet temperature of cold fluid (Table 4).

Table 4. Creating meshes and obtained temperatures

		Mesh Metrics		**Mesh Properties**		**Outlet temperature of the cold fluid (K)**
Meshes	Skewness	Orthogonal quality	Element quality	Element number	Grid number	
Mesh-I	0.2112	0.9321	0.8655	854478	1172006	303.75818
Mesh II	0.2317	0.9172	0.8213	386500	551447	303.49885
Mesh-III	0.3240	0.8346	0.7175	144622	216384	303.05698

As can be seen from the Table 4 that the outlet temperature of the cold fluid not change much for 3 different mesh types. It is a well-known fact that the accuracy of the solution rises as element and grid numbers increase. However, the number of element and grid numbers directly affected the solution time. So, mesh-II was chosen for calculations.

5. Conclusion

In this numerical study, performance of the heat wheel rotating at 10 rpm has been investigated. A solid model of the heat wheel has been constructed and analysed via ANSYS Fluent™ software. Angular velocity of 10 rpm has been widely used in experimental studies [1]. Therefore, the performance of the system is determined operating the wheel at 10 rpm angular velocity. The outcomes that can be drawn from this study and suggestions are as follows:

- The heat wheel is roughly 1.5-fold more efficient when it is rotated.
- The more equal heat dissipation is attained in the transient mode (10 rpm) than that of steady state (0 rpm-stationary) mode.
- The maximum heat transfer is actualized in the outlet zone of exhaust air. The temperature difference at this zone is 5.79 K.
- The effectiveness of the heat wheel is found for the steady and transient analysis 52.62 % and 32.42 %, respectively. Similarly, the effectiveness of the heat wheel operating at 10 rpm was found as about 62% by Zhang [1].
- The differences between these values can be derived from the solution methods and/or measurement errors.
- Adsorbent materials, which are of low thermal conductivity and high specific capacity, can be easily used to enhance the heat transfer efficiency of regenerative heat exchangers.
- Using different adsorbent materials, both experimental and numerical studies could be performed.
- The importance of the numerical study for the solution of a complex problem was understood.

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