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Determination of Optimum Rotational Speed of the Heat Wheel through Computational Fluid Dynamics Simulation

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Abstract

Heat wheel is a kind of regenerative heat exchanger mostly used in Heating, Ventilation and Air Conditioning (HVAC) systems for two main goals; energy recovery from the waste heat and /or dehumidification of the air. Performance of the heat wheel utilized merely for energy recovery has been numerically investigated in this study. For the aim of determining the optimum rotational speed, three different angular velocities have been used under the transient conditions. The findings obtained from the analysis have been compared to a validated experimental study in literature. Consequently, it has been observed that they are in good agreement each other.

1. INTRODUCTION

Increasing energy demand and the pollution have triggered the scientist to overcome these problems; therefore, they have inclined to develop new materials and equipment. According to a report published recently, an increase of 47% in the world's energy consumption is participated to occur until 2035. Carbon emissions have also been increasing gradually since 1900s [1]. As a result, energy efficiency studies have gained more importance than ever before.

There are variety of different processes employed for the aim of energy efficiency like heat recovery, insulation, making use of nano technological materials and so on. However, energy efficiency by recovering the waste heat and used this recovered heat in a discrete process is mostly used application in the energy systems. In these applications, generally, the working fluid is directed to a heat recovery unit located in the system after it completes its due and thus the heat transfer between two fluids makes possible. Nowadays, newly emerging regenerative heat exchangers, heat wheels, have been begun to use in place of conventional heat recovery systems. The heat wheels have been used in many processes ranging from electric generation to air purification for energy recovery and/or air dehumidification. They are also called as energy wheel, desiccant wheel or rotary adsorbent bed type heat exchanger [1]. These heat exchangers allow simultaneous heat and mass transfer, which makes them superior. A number of micro channels located within a heat wheel provide the heat and/or mass transfer to take place expeditiously.

1.1. Literature Review

In this study, performance analysis of the heat wheel has been performed using Computational Fluid Dynamics (CFD) approach. Energetic performance of different type heat wheels has been investigated by varied analysis methods. While some scientists have investigated the heat wheel performance with only theoretical analysis, others have been used theoretical and experimental analysis together. They have

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composed some mathematical models presenting operating conditions of the heat wheel and have examined the heat wheel performance theoretically [2-6]. Different from these analytical works, analytical and experimental methods have been used together in some studies. Put it differently, a mathematical model has been created and applied to an experimental setup [7-9]. Besides, there are some studies in literature in which only numerical methods like finite difference method have been used for determining the performance of the heat wheels. To illustrate; Zhang et al. (2010) investigated the heat transfer and pressure drop in sinusoidal shaped channels under hydrodynamically full developed and thermally developing flow conditions at the equal temperature values. They calculated such dimensionless numbers as Reynolds number, local and mean Nusselt numbers and also indicated that obtained values could be used for performance analysis of the honeycomb shaped regenerative heat exchangers [10]. Sphaier and Worek (2005) constituted a new mathematical model assuming heat and mass transfers in desiccant wheel realizes in two dimensions (axial and radial) and numerically solved their model. They also computed the alteration of some parameters presenting the axial diffusion (Biot number, rotation speed etc.). They expressed that their study gave information regarding whether axial diffusion occurs or not [11]. Ruivo et al. (2011) numerically investigated the influence of atmospheric pressure on the heat and mass transfer rates in desiccant wheels. Process and regeneration air velocities were taken fixed and silica gel was used as the hygroscopic material in their study. They observed that heat and mass transfer rates were few when air velocities were small [12]. Wu et al. (2006) analyzed the influence of heat conduction in the direction of the fluid flow and the impact of variations in rotating speed of the wheel as well as other such characteristics as ambient temperature, airflow and geometric size on dynamic responses. Their study was based on three test cases for variable frequency, input temperature and volumetric airflow. They reported that the frequency of the wheel has an effect on the output temperature, and the faster the rotating speed, the higher the temperature of the heat wheel. In addition, they stated that the starting point and the steady-state value changed accordingly to the input temperature of the extracted and supply air [13]. Also, some related studies were conducted to determine the heat wheel performance used for different objectives. [14-20].

When these various works related to heat wheels were investigated, it was seen that analytical methods were remained incapable and the number of numerical studies was limited. Moreover, effect of the rotational speed on the thermal performance was numerically analyzed under steady-state conditions in few studies [10,13]. Therefore, the impact of rotational speed, i.e. angular velocity, on the performance parameters of the heat wheel has been examined under transient conditions using CFD approach in this work. Additionally, different from related studies in literature, a novel model titled "channel circle" has been designed and utilized for numerical analysis in this study. Thermophysical properties of adsorbent material has been identified onto the software. Three different rotational speed values have been used and findings have been compared to each other to determine optimum rotational speed. Furthermore, no other study using Dynamic Mesh Method has been encountered in the literature. By these aspects of work, it has been aimed to be a pioneer and present an idea in future works. The boundary conditions for this study have been formed utilizing the operating conditions of an experimental study realized by Zhang [1] and gained findings have been compared to experimental results.

2. MATERIAL AND METHOD

2.1. Heat Wheel

Heat wheel is a heat and mass exchanger in which the working fluid is air and it has parallel and counter current flow order (Figure 1). That kind of devices have emerged due to the requirement of continuous working of the adsorbent beds. Heat transfer in heat wheels actualizes indirectly. There is an adsorbent material like silica gel and lithium chloride coating all channels of the heat wheel and it allows heat transfer realizes quickly. In these heat exchangers, the heat of hot fluid adsorbs by adsorbent material and then transfers to cold fluid perpetually by means of rotation of the adsorbent bed.

It is a well-known fact that stationary adsorbent beds need an extra fluid passage to regenerate the system. However, rotary adsorbent beds can easily be regenerated by means of the rotation of the system at constant speed. Other priorities of the heat wheels are as follows:

- They are of both high effectiveness and low-pressure drop.
- Initial investment cost of them is small.
- It is easy for them to clean oneself.
- They might have very high compactness ratio (up to 16000 m^2/m^3).

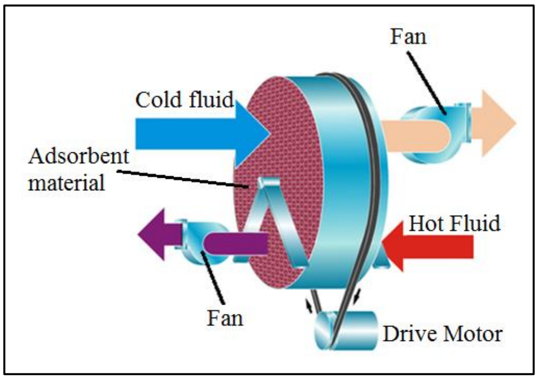

Figure 1. *Schematic view of the heat wheel*

Apart from the advantages of the heat wheels mentioned above, some drawbacks can cause not to use them. For example, they operate with only gas fluids and working fluids can mostly intermingle in the system.

2.2. Constitution of CFD Model

Computational Fluid Dynamics numerical solving method has been utilized in this work. This method has been used since 1970s to clarify the flow, heat and mass transfers problems mostly encountered in engineering. In the CFD approach, a solving zone (generally a control area or control volume) is chosen and a group of differential equation defining the movement of the fluid (Navier-Stokes Equations) is solved for that chosen zone. These zones are named in CFD studies as grid or mesh (Figure 2). With the help of this solving method, one can be readily obtained the information relating flow area like shear stress, velocity vectors, pressure and temperature distributions and streamlines. Nonetheless, it is unable to get these from an experimental or theoretical study. In addition, comparison and verification of the findings acquired from a number of CFD analysis to similar experimental and theoretical studies contribute to alleviate the required test number.

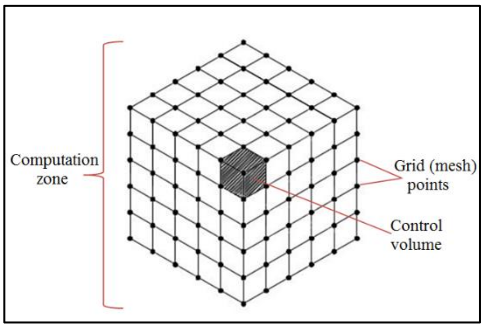

Figure 2. *The elements in a 3D meshing*

The first thing to do in CFD analysis is to build up a solid model. That model not only must contain all specifications of the problem, but also should be simple to be analyzed easily. Then, a meshing is generated and all boundary and operating conditions are identified to model. The equations aforementioned are subsequently solved on grids. The obtained results, finally, are viewed to investigate the alteration in examined model.

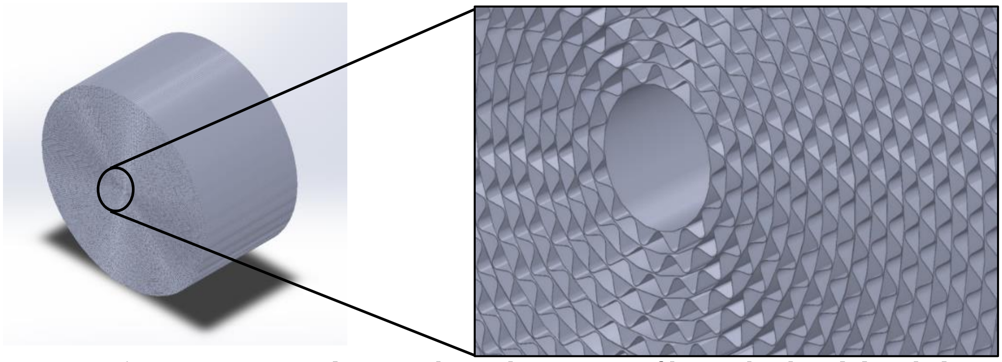

Figure 3. *Consisted micro channel geometry of heat wheel and detailed view*

Heat wheels have very complex geometry due to the fact that they have a plenty of micro channels (Figure 3.). It is too hard to numerically determine the heat wheel performance as whole system. Although it is possible, the solution can last for days. Hence, it has been preferred to analyze just a part or a channel of it and previous studies have confirmed the results of this attitude.

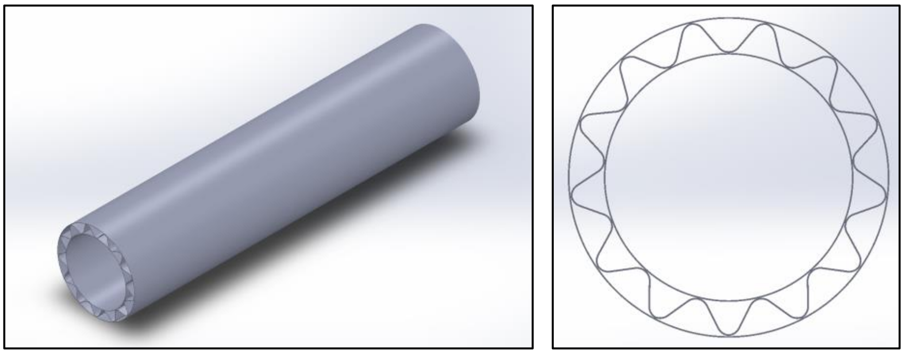

Figure 4. *Isometric and front views of channel circle*

Unlike former works, a novel type model named as channel circle and presented the real model completely has been designed and analyzed with ANSYS Fluent software under transient conditions. Channel circle is an annulus shaped geometry composed by the micro channels located on a circle of heat wheel (Figure 4). The properties of both real and simplified model, that is channel circle, can be seen in Table 1.

Table 1. *Properties of the created models*

Specifications / Model type	**Real model**	**Simplified model**
Wheel diameter (mm)	300	17 / 22 (inner/outer)
Channel geometry	Sinusoidal	Sinusoidal
Channel width (mm)	2.5	2.5
Thickness of channel material (mm)	0.12	0.12
Wall thickness (mm)	1.9	1.9
Channel length (mm)	100	100

The analyzed model has included 13 channels and the behaviors of them have been examined under time dependent solution conditions. Before embarking upon the analysis, meshing has been realized with 551447 nodes and 386500 elements. The mesh views of the channel circle have been given in Figure 5. The mesh metrics displaying the mesh quality have also been depicted in Table 2. It can be seen from the table that meshing quality is an acceptable level.

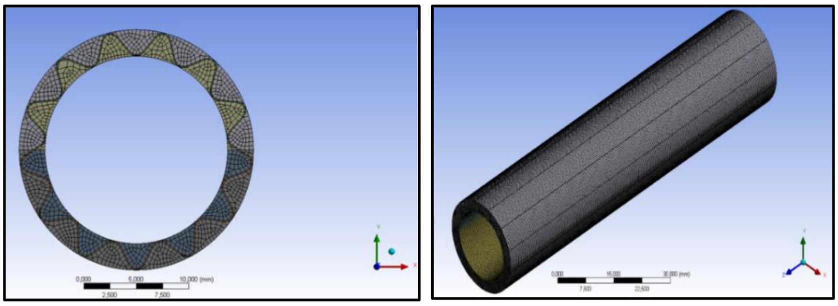

Figure 5. *The meshing model of the channel circle*

Table 2. *Mesh metrics of the model*

Parameters	Minimum value	Maximum value	Average
Skewness	1.3057	0.9388	0.2317
Orthogonal quality	0.1107	1	0.9172
Element quality	0.1020	0.9989	0.8213

When it comes to run the solution, all boundary and operating conditions monitored in Table 3 have been entered onto the software. The time-dependent (transient) solution also has been activated and Dynamic Mesh Module (DMM) of the software has been used to identify the rotational speed. The Sliding Mesh Method (SMM) which is a solution technique situated in DMM has been utilized to describe the rotation to the model [21].

Table 3. *Boundary and operation conditions*

Boundary / Operating Conditions	Value
$T_{1,i}$ (K)	308.15
$T_{2,i}$ (K)	297.15
Inlet velocity of process air(m/s)	3.8
Inlet velocity of exhaust air (m/s)	3.8
Gravitational acceleration (m/s^2)	9.81
Time step size (s)	0.005

The numerical solutions have been run under the condition of pressure-based solver. Gravity has also been taken into account. PRESTO!, Second Order Upwind and Second Order Implicit numerical solution methods have been preferred for all analysis. In order to obtain more accurate results, time step size has been set to 0.005 s. Because the more the time step size is, the more accurate the findings are obtained. However, this case is limited by computational time and system requirements. The results for different locations have been achieved by adjusting the number of time steps. To put it bluntly, for 10 rpm rotational speed, number of time steps has been set to 1200 for viewing the results at 180° turned state since heat wheel completes one period in 6 seconds.

The analysis have been made for 3 varied rotational speed; namely 5 rpm, 10 rpm and 15 rpm, respectively. All other conditions have been kept constant during analysis. The system operation has been investigated and graphically demonstrated for eight different locations ranging from 45° to 360°.

The efficiency of the heat wheel (ε) has been calculated by dividing the $\dot{Q}$ to $\dot{Q}_{max}$ (Eq. 1). $\dot{Q}$ represents the realized heat transfer rate in heat wheel, while $\dot{Q}_{max}$ represents the maximum (realizable) heat transfer rate under the same conditions.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \tag{1}$$

$$\dot{Q} = C_1(T_{1,i} - T_{1,o}) = C_2(T_{2,i} - T_{2,o}) \tag{2}$$

$$\dot{Q}_{max} = (C_1, C_2)_{min}(T_{1,i} - T_{2,o}) \tag{3}$$

C is the thermal capacity flow rate and equal to $\dot{m}c_p$. C is constant for all calculations because of the fact that both heat capacity and mass flow rates of each fluid are the same. Therefore, it is enable to rewrite the Eq. 1 as follows:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{T_{1,i} - T_{1,o}}{T_{1,i} - T_{2,o}} \tag{4}$$

2.3. Mesh Independency

In CFD solutions, analysis results must be independent from the meshing properties like element size, element type, the number of element and so on. That is, the results must remain almost the same even if meshing parameters have been changed. Therefore, meshing independency must be conducted before obtaining the results.

The mesh independency has been realized by comprising three different element numbers and the analysis have been performed using the mentioned element numbers in this work. Investigating the alterations in 10-rpm analysis results for cold fluid outlet temperatures, mesh independency has been confirmed.

Table 4. *Mesh parameters and cold fluid outlet temperatures for created mesh models*

Mesh Models	Meshing Quality Indicators			Mesh Parameters		Cold fluid outlet temperature (K)
	Skewness	Orthogonality	Element quality	Number of elements	Number of nodes	
Mesh model-I	0.2112	0.9321	0.8655	854478	1172006	303.75818
Mesh model-II	0.2317	0.9172	0.8213	386500	551447	303.49885
Mesh model-III	0.3240	0.8346	0.7175	144622	216384	303.05698

Mesh parameters for each element number and the cold fluid outlet temperatures can be seen in Table 4. Table 4 bluntly shows that there are no considerable changes in cold fluid outlet temperature values, although the number of elements changes remarkably.

3. RESULTS AND DISCUSSION

Numerical solutions have been conducted using the same boundary conditions as ref. [1] in order to validate the created model. In Table 3, both boundary and operating conditions have been presented. Besides, all conditions aforementioned remain the same, even though the rotational speed changes. That said, silica gel has been used as adsorbent material for all conditions. The thermophysical properties of it can be seen in Table 5.

Table 5. *Thermophysical properties of adsorbent material (Silica gel-Type A) [22]*

Material Properties	Silica gel (Type A)
Thermal Conductivity ($Wm^{-1}K^{-1}$)	0.174
Density (kgm^{-3})	730
Specific Heat ($Jkg^{-1}K^{-1}$)	921
Mean Pore Diameter (nm)	2.2
pH	5

When it comes to exposition of the findings, equally spaced six iso-surface have been created and mean temperature value of each has been computed on software. These iso-surfaces can be seen in Figure 6.

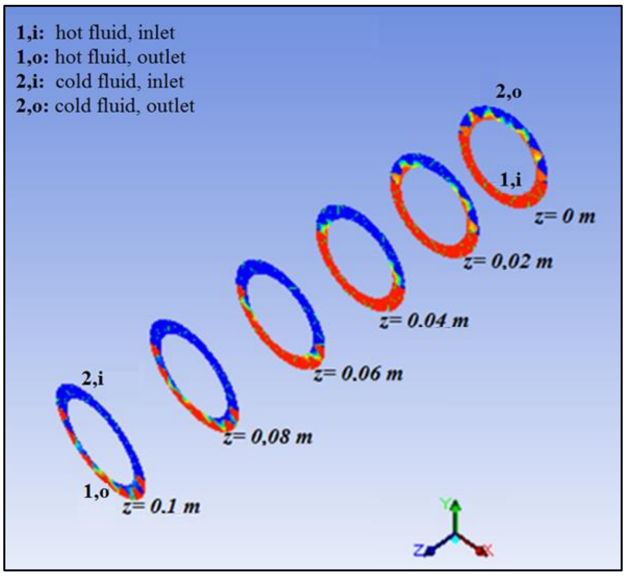

Figure 6. *Created iso-surfaces and their locations*

In the first analysis, heat wheel has been rotated at 5 rpm rotational speed. It has been obtained from the analysis that the maximum efficiency of the heat wheel is 41.9 %. Efficiency values, in addition, have been calculated using Eq. 4 for all rotation speeds. For 5 rpm rotational speed, efficiency is

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{T_{1,i}-T_{1,o}}{T_{1,i}-T_{2,o}} = \frac{301.75842-297.15}{308.15-297.15} = 0.419 \quad (5)$$

Temperature distributions at 360° turned state, for 5 rpm, have been given in Figure 7 to understand the results better.

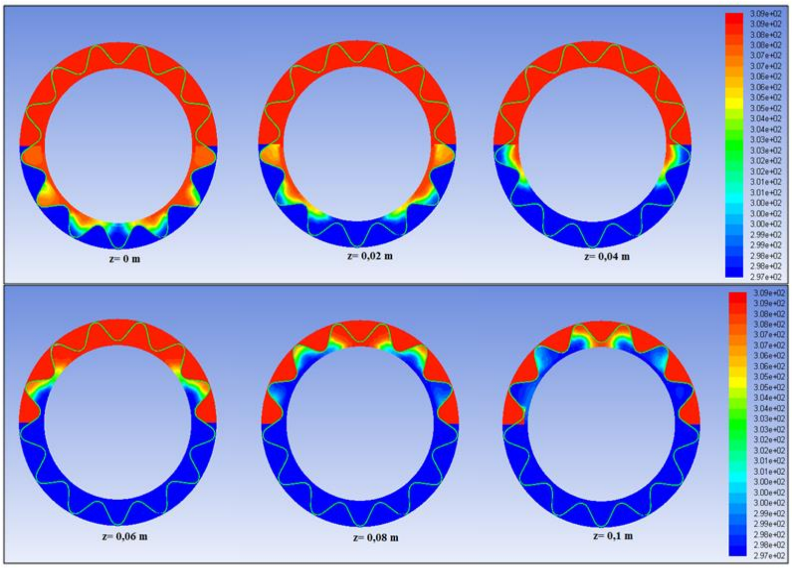

Figure 7. *Temperature changes at 360° turned state (N=5 rpm)*

Similarly, the heat wheel has been rotated at 10 rpm and 15 rpm rotational speeds, respectively. The findings obtained from these analyses can be seen in Figure 8 and Figure 9.

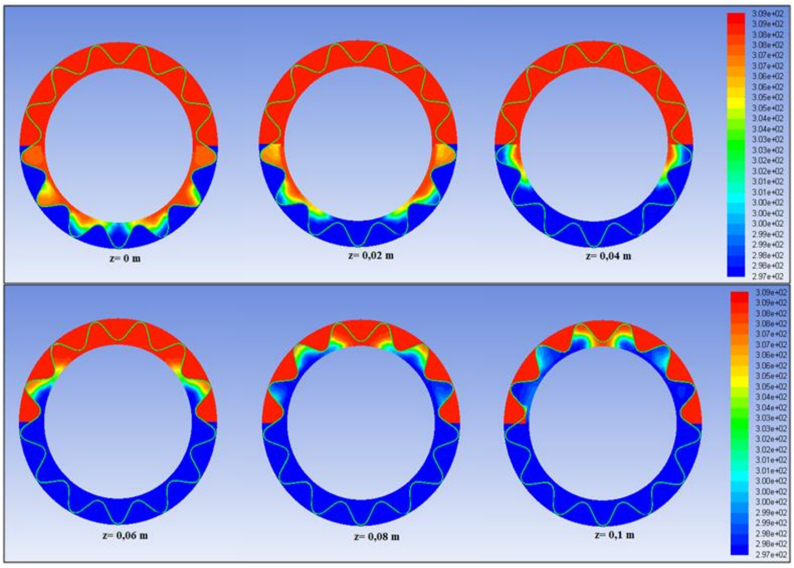

Figure 8. *Temperature changes at 360° turned state (N=10 rpm)*

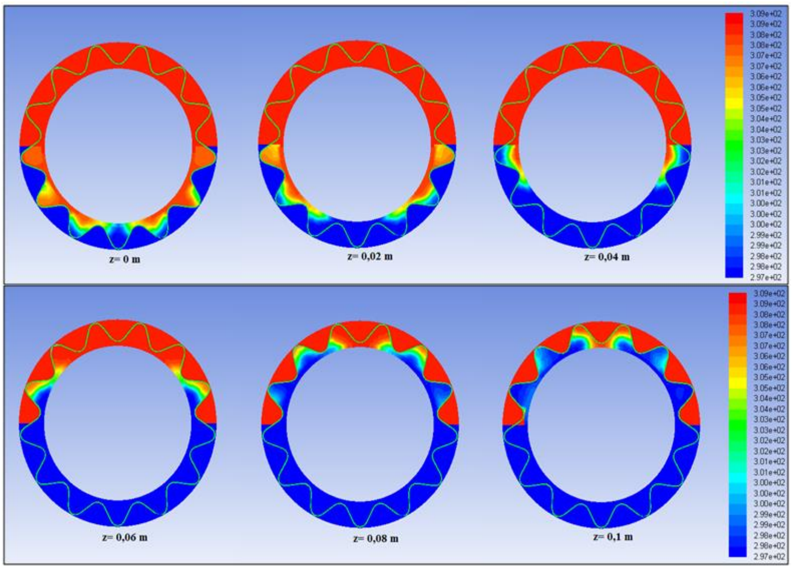

Figure 9. *Temperature changes at 360° turned state (N=15 rpm)*

The maximum efficiency values of the heat wheel have been obtained as 57.7 % for 10 rpm (Eq. 6) and 47.4 % for 15 rpm (Eq. 7) rotational speed.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{T_{1,i}-T_{1,o}}{T_{1,i}-T_{2,o}} = \frac{303.49885-297.15}{308.15-297.15} = 0.577 \qquad (6)$$

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{T_{1,i}-T_{1,o}}{T_{1,i}-T_{2,o}} = \frac{302.35827-297.15}{308.15-297.15} = 0.474 \qquad (7)$$

Mean outlet temperature values of hot and cold fluids for different locations have been demonstrated as tabular and graphically in Table 6 and Figure 10, in turn.

Table 6. *Mean outlet temperatures of hot and cold fluid for varying locations*

Locations					
Rotational speed (rpm)	**Temperature (K)**	**45°**	**90°**	**135°**	**180°**
5	$T_{2,o}$	300.73270	301.71667	300.73114	301.71826
	$T_{1,o}$	302.70224	303.72855	302.70377	303.72687
10	$T_{2,o}$	301.73135	303.71790	301.73132	303.71793
	$T_{1,o}$	302.70328	301.72629	302.70340	301.72638
15	$T_{2,o}$	301.73123	302.71564	301.73123	302.71722
	$T_{1,o}$	302.70325	301.72696	302.70328	301.12565
Locations		**225°**	**270°**	**315°**	**360°**
5	$T_{2,o}$	300.73245	301.71808	300.7323	301.75842
	$T_{1,o}$	302.70245	303.72699	302.70251	303.69043
10	$T_{2,o}$	301.73273	303.71793	301.73270	303.49885
	$T_{1,o}$	302.70203	301.72635	302.70206	301.98965
15	$T_{2,o}$	301.73254	302.71713	301.73248	302.35827
	$T_{1,o}$	302.70206	301.72565	302.70206	301.98672

It can be seen from the results that the maximum efficiency has been obtained when heat wheel has been rotated at 10 rpm rotational speed. This result is in compliance with ref. [1] (Table 7). That is, numerical study results have been in good agreement with experimental results. Also noting that the efficiency values have changed with the same trend for either study (Figure 10).

Table 7. *Efficiency values for performed and reference studies*

Efficiency	**Rotational speed (rpm)**		
	5	**10**	**15**
Performed study	0.419	0.577	0.474
Zhang [1]	0.51	0.62	0.59

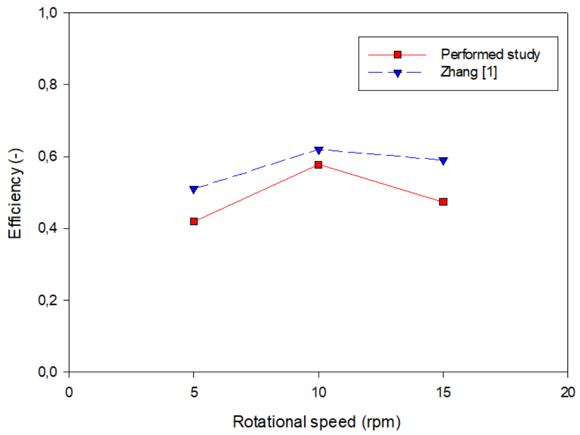

Figure 10. *Comparisons of heat wheel efficiency values for varying rotational speeds*

4. CONCLUSION

A heat wheel performance used for enthalpy recovery applications has been numerically determined in this work. A novel model approach has been used and analyzed in a CFD code (ANSYS Fluent) by employing the experimental data of ref [1]. The main consequences inferred from this numerical study and some implications are as follows:

- Once more be proved that the efficiency of the heat wheels is strongly influenced by the rotational speed and there is an optimum rotational speed for each of them.
- The efficiency of the analyzed heat wheel has been achieved as 41.9%, 57.7 % and 47.4% for 5, 10 and 15 rpm rotational speed, respectively.

- When the results of this study compared to experimental data, the error rate for optimum rotational speed has been 7% and it is thought that is is derived from the cutting and truncation errors.
- A type Silica gel has been used as the adsorbent material and inlet velocity of the both flow passages has been equal. In future studies, different adsorbent materials and varying flow passage velocities can be used to determine the influences of material and flow passage velocity on the efficiency.
- The maximum heat transfer rate has been obtained when heat wheel has rotated at 10 rpm, i.e. optimum rotational speed.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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