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# Development of rotary heat exchanger model to investigate performance with integrating controller

A M Ghoneim<sup>1,4</sup>, M H Aly<sup>2,4</sup> and O E Mahmoud<sup>3,4</sup>

<sup>1</sup> Demonstrator. <sup>2</sup> Lecturer. <sup>3</sup> Assoc. Prof.

<sup>4</sup> Mech. Power Eng. Dept., Fac. Of Eng. Mataria, Helwan University, Egypt.

[ahmedghoneim014@gmail.com](mailto:ahmedghoneim014@gmail.com)

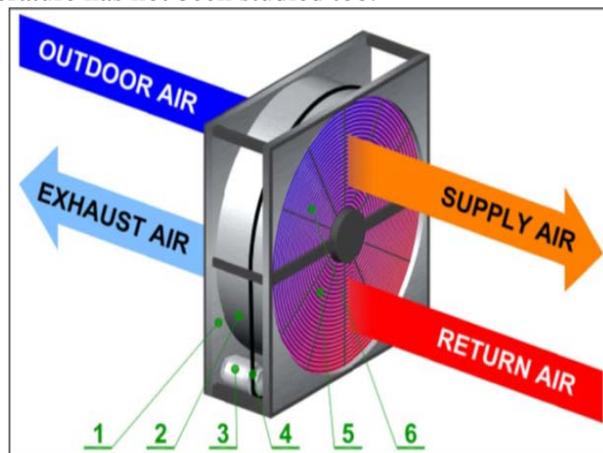
**Abstract.** The heat wheel considers one of the best heat recovery devices with very high effectiveness, which leads to great savings in energy and operating expenses. This research study a novel dynamic model of a rotary heat exchanger automatically control the temperature of outlet air despite the operating conditions are changed. The model is implemented under MATLAB/SIMULINK environment to investigate the performance of the heat wheel considering the air properties changing during the operation. The transient effect of air-flow rate, inlet air temperature and wheel rotational speed on the output temperature and effectiveness are discussed. The optimum rotational speed of a heat wheel was investigated for different operating conditions. The temperature distribution of air and matrix for one Full cycle of heat wheel were investigated. The model was validated based on data found in previously published experimental work. Results reveal that the effectiveness of the device is inversely proportional to the amount of flow, while it is directly proportional to the rotational wheel speed. The effectiveness is slightly affected by the inlet air temperature.

## 1. Introduction

A large part of building energy is consumed in the process of air conditioning to achieve comfortable and healthy conditions. Energy loss in the ventilation process leads to an increase in energy costs needed to maintain the required indoor conditions. To reduce the losses, a device is needed that can transfer energy from the exhaust air to the fresh air [1]. Utilizing heat recovery facilities can improve the system efficiency by recovery the escaped energy. The estimations show that more than 70% of the escaped energy can be recovered [2]. Heat wheels have many applications such as air conditioning, gas turbine system, flue gas desulfurization, and thermal power plant systems [3]. One of the main advantages of the heat wheel is high effectiveness, exceeds 80% [4]. Figure 1 shows a schematic diagram of a heat wheel. While the wheel rotates, energy transfers from the hot airstream to the wheel, then energy transferred to the cold air stream from the stored energy in the wheel as the wheel rotates 180° [5]. Diverse experimental and theoretical investigations have examined the heat wheel to assess its effectiveness. Some investigations studied the heat transfer process within the wheel flow channels by applying the partial differential equation model under simplified assumptions [6,7]. However, due to solutions inaccuracy and complexity, the results were not used by rotary heat exchanger manufacturers and designers. Instead, most of the dependable results are in the form of correlations studied by Kays and London [8]. They proposed a correlation based on the results of a complete study on heat wheels done by Lamberston [9], Bahnke and Howard [10]. Kays and London's correlation gives dependable results for rotary heat exchanger performance to high rotational speeds only. Yilmaz and Buyukalaca provide an analytical solution for the performance of rotary heat exchanger [11,12] which can be useful for any wheel rotational speed. No one of the previous studies has presented the



transient air temperature variations of the heat wheels. Also, the effect of integrating of control system target the outlet air temperature has not been studied too.



**Figure 1.** Schematic diagram of a counter flow heat wheel: 1—housing, 2—rotor, 3—electric motor, 4—belt, 5—return airside, 6—supply air side [13].

In this search, the modelling of the heat wheel was performed considering the changing of air properties during the operation. The model validation was done by comparison with previously published experimental work. The transient effect of air-flow rate, inlet air temperature and wheel rotational speed on the output temperature and effectiveness are discussed. Besides, an automatic control system is designed using the rotary heat exchanger model to regulate the outlet air temperature from heat exchanger despite operating conditions are changing.

## 2. Mathematical model

### 2.1 Describe the Heat Wheel and Simplifying Model Assumptions

This section briefly studied the mathematical model for the heat wheel dynamics. A rotary heat exchanger can be presented as a frequent flow type heat exchanger. Any channel in the wheel is periodically passed from the hot air to the cold air while the wheel is continuously rotating. The wheel is located between air channels air with counter flow directions. To simplify the problem, the following simplifying assumptions are made:

1. The flow is deemed as one-dimensional flow and is incompressible.
2. The channels that make up the heat wheel are equal with constant heat transfer surface areas.
3. The channels are treated adiabatic and impermeable.
4. The air heat conduction is negligible.
5. The effect of drop pressure along the channel is negligible.
6. The rotary heat exchanger includes no work exchanges so that potential and kinetic energy differences for gas are negligible.
7. The matrix thermodynamic and physical properties are considered as constant.

Based on the above assumptions, the model used in this paper is transient and one-dimensional. One of the channels is split into a finite number of equal discrete elements or channels perpendicular to the flow directions (as shown in figure 2) and each discrete element contains control volume from the air and matrix as shown in figure 2. A rotary heat exchanger can be presented as a finite number of channels along the circle that the wheel traverses during a whole cycle to investigate the performance of the heat wheel through a full cycle as shown in figure 3.

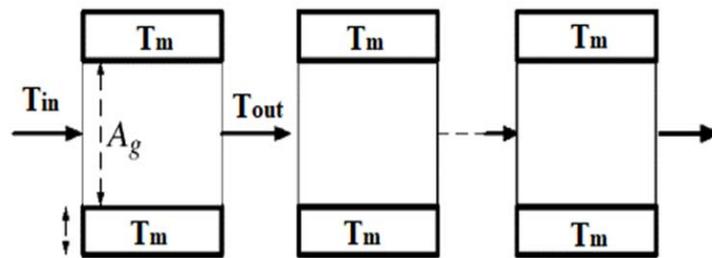


Figure 2. Schematic diagram of a discrete channel.

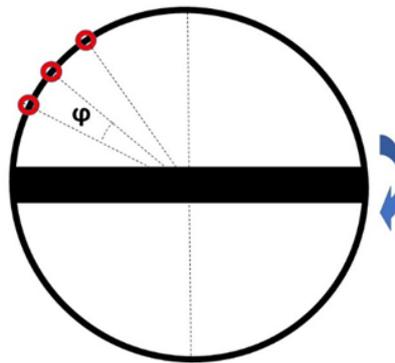


Figure 3. Schematic diagram of a finite number of channels along the cycle around the wheel.

## 2.2 Governing Equations

The following equations are applied to each discrete element of the channel: Conservation of energy in the air stream, conservation of energy in the solid wall.

Heat transfer equation for the airstream:

$$\rho_g A_g dz C_p \frac{dT_g}{dt} = U_g A_g \rho_g C_p T_{g_{in}} - U_g A_g \rho_g C_p T_{g_{out}} - h_{HT} p dz (T_g - T_m) \quad (1)$$

$$U_g = \frac{v f}{\sigma}, \sigma = \frac{A_g}{A_g + A_m}$$

$$\frac{dT_g}{dt} = \frac{U_g}{dz} (T_{g_{in}} - T_{g_{out}}) - \frac{h_{HT} p}{\rho_g A_g C_p} (T_g - T_m) \quad (2)$$

Heat transfer for wall:

$$\rho_m A_m dz C_m \frac{dT_m}{dt} = \frac{k A_m}{dz} (T_{m_p} - T_m) - \frac{k A_m}{dz} (T_m - T_{m_f}) + h_{HT} p dz (T_g - T_m) \quad (3)$$

$$A_m = p \cdot \frac{s}{n}$$

$$\frac{dT_m}{dt} = \frac{k}{\rho_m C_m dz^2} (T_{m_p} + T_{m_f} - 2T_m) + \frac{h_{HT} p}{\rho_m A_m C_m} (T_g - T_m) \quad (4)$$

The Nusselt number is used to calculate the heat transfer coefficient as follows:

$$h_{HT} = \frac{Nu \cdot k_g}{D_h} \tag{5}$$

To consider the changing temperature and air velocity profiles along the channel, the local Nusselt number is calculated through the following correlation [14].

$$Nu = Nu_{FD} + \frac{0.0841}{0.002907 + Gz^{-0.6504}} \tag{6}$$

$$Gz = \frac{L/D_h}{Re \cdot Pr}, \quad Re = \frac{\rho_g U_g D_h}{\mu_g}, \quad Pr = \frac{\mu_g C_{p_g}}{k_g}$$

where  $Nu_{FD}$  is the Nusselt number for the fully developed flow and its value depends on the channel geometry. This is presented in Table 1 for typical axial symmetric flow channel geometries [15] and in figure 4 for sinusoidal channels [16].

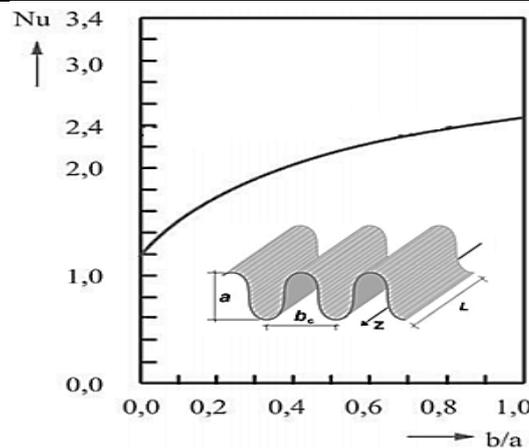
In order to take the effect of temperature changing during the operation on the air properties, the thermodynamic properties of air are evaluated through the following correlations [17].

$$\rho_g = \frac{351.99}{T_g} + \frac{344.84}{T_g^2}, \quad k_g = \frac{2.3340 \cdot 10^{-3} T_g^{3/2}}{164.54 + T_g}, \quad \mu_g = \frac{1.4592 \cdot 10^{-6} T_g^{3/2}}{109.10 + T_g}$$

$$C_{p_g} = 1030.5 - 0.19975 T_g + 3.9734 \cdot 10^{-4} T_g^2$$

**Table 1.** Fully developed Nusselt Numbers for Many Axial Symmetric Channels.

Channel Shape					
$Nu_{FD}$	7.54	2.35	2.89	3.44	3.66



**Figure 4.** Nusselt Number at Fully Developed Air-flow in Sinusoidal Channels.

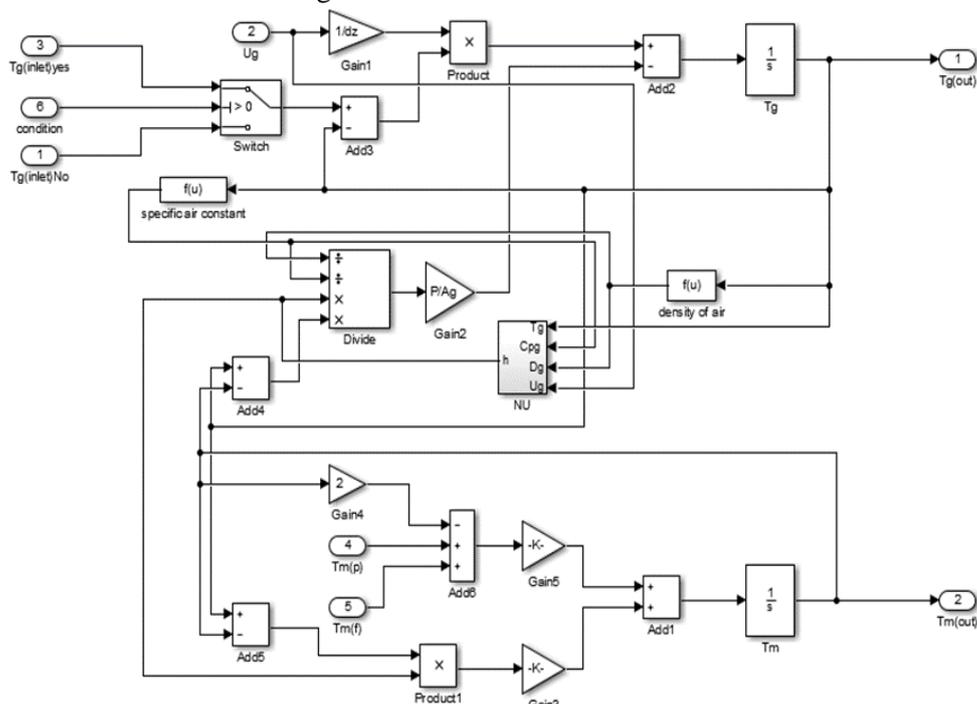
Finally, the heat wheel effectiveness should be calculated as the main parameter that was commonly used to evaluate the performance of the heat exchanger. The heat wheel effectiveness is:

$$\varepsilon = \frac{(T_{h,in} - T_{h,out}) + (T_{c,in} - T_{c,out})}{2(T_{h,in} - T_{c,in})} \tag{7}$$

### 2.3 Implementation in Simulink

Simulink is an environment integrated with MATLAB and is used for simulation of dynamic systems, which provides access to a wide range of tools for numerical computations [18]. Simulink has block libraries with numerous standard operations that allow you to build your own blocks. Blocks are linked through the input and the output ports to form dynamic system models. Simulink provides many solvers that support the developers in getting up the equations for the dynamic systems. Simulink is intuitive and flexible for the programmer by a very flexible graphical interface with respect to the systems of equations that are able to handle them [19].

The model of heat wheel has been built up based on the main framework for each segment shown in figure 2 that can be regarded as two main subsystems (air subsystem and matrix subsystem), that affected by each other. In figure 5, a block diagram shows the simulation of one segment from the air channel of the rotary heat exchanger. The segments are linked through input and output ports to represent an air channel consisting of several segments. Figure 6 displays a sample of a Simulink model for an air channel. For simulating the rotation of the wheel, the input air temperature and flow speed are periodically changed from the warm air to the cold air, so a block diagram has been built up and jointed to the main framework for each segment. Figure 7 shows a Simulink block for a periodically changed from the warm air to the cold air. The change between the hot period and cold period of all air channels is carried out sequentially by a delay equal to the difference in angle between the channels taking into account that the flow direction in the hot period is opposite the flow direction in the cold period. The time each channel passes through the air stream can be counted to estimate the output conditions in the various angles for the wheel.



**Figure 5.**Block diagram for one segment.

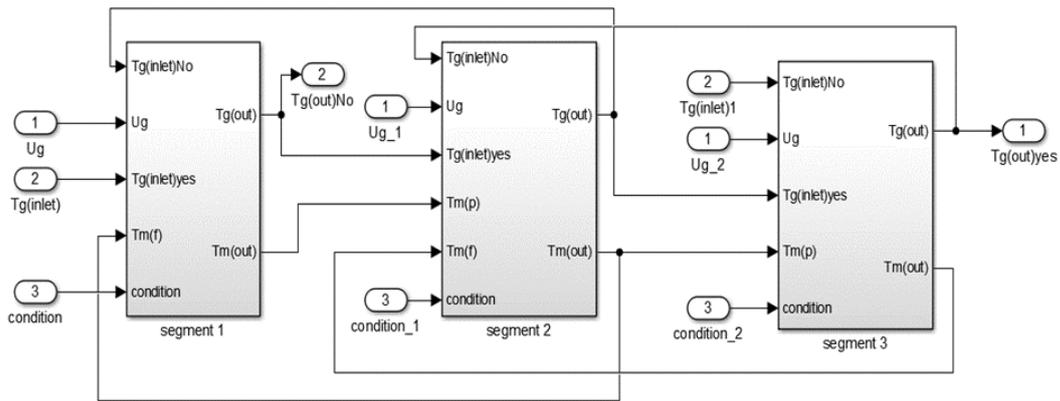


Figure 6. Block diagram of channel model

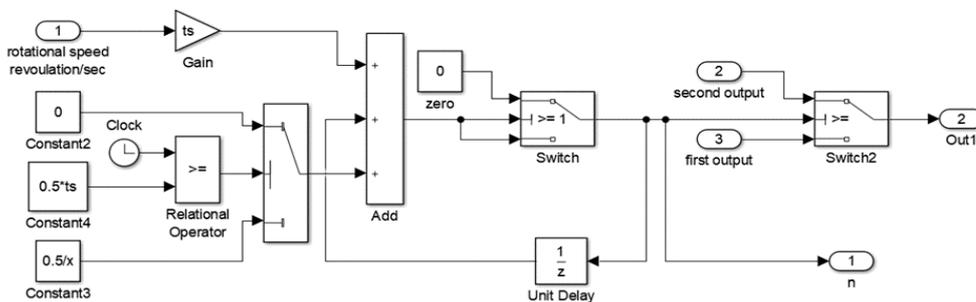


Figure 7. Block diagram for rotation motion.

2.4 Model validation

The numerical simulation has been compared with the published actual values of an experimental work [20-22]. The model has been verified in numerous working conditions with different air-flow rates and inlet air temperature of both air streams and revolution speed. The validation of the model results with the experimental data and a good agreement among model result and experimental data is achieved. In figure 8 the validation of the model results with the experimental actual results. The extreme relative error among the model results and the experimental data is continuously lesser than 5%. The response of the dynamic model based on changes in control inputs has been compared with the published actual values, in figure 9. The simulation results and the experimental actual dates are in good agreement in terms of steady-state values and temperature trends. Consequently, it is probable to say that the mathematical model can fine predict the performance of the heat exchanger.

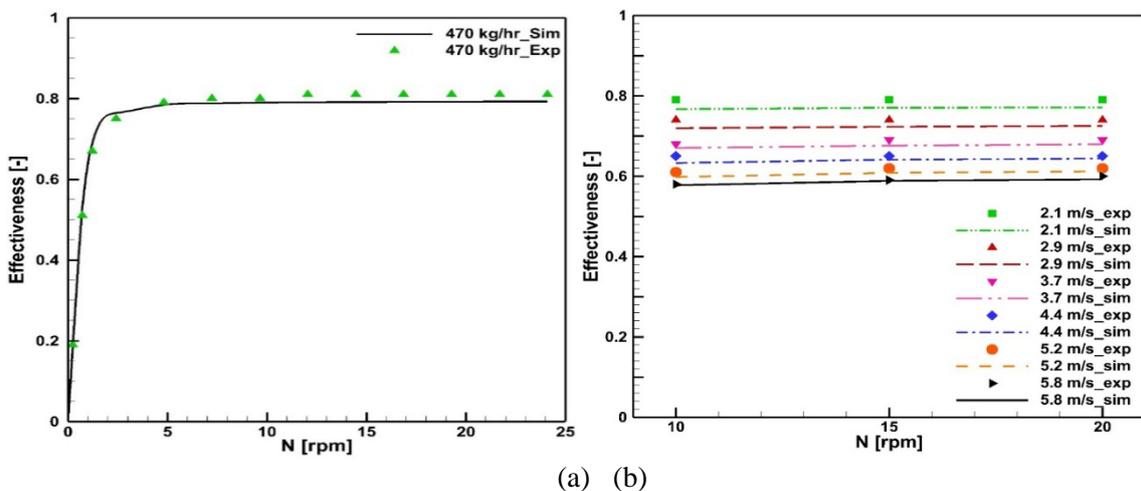
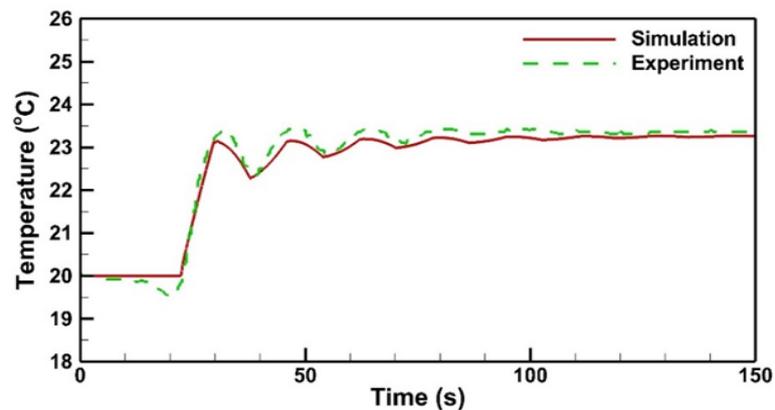


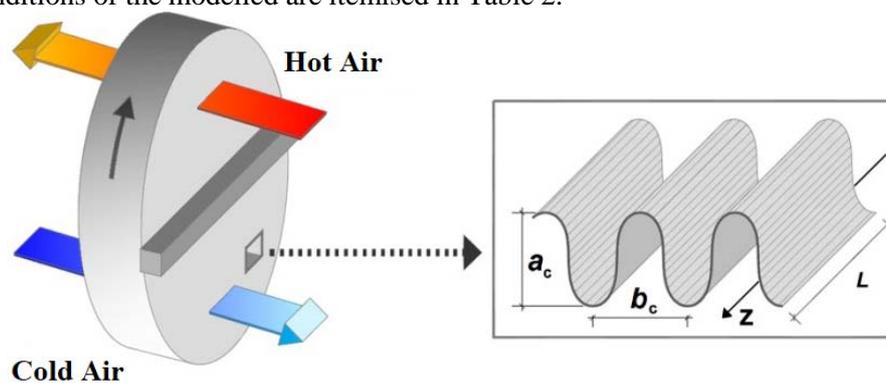
Figure 8. Validation with experimental data.



**Figure 9.**Outlet cold air temperature versus time with a step increase to wheel speed.

### 3. Results and discussion

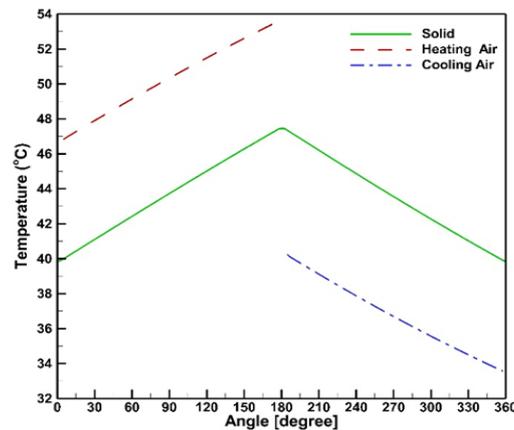
The research has been displayed a heat wheel with corrugated sinusoidal ducts as it the most well-known in heat wheels due to having large heat transfer surface area and the simplicity of construction (figure 10). Geometric properties, the material for the matrix with thermophysical characteristics and operating conditions of the modelled are itemised in Table 2.



**Figure 10.**Scheme of heat wheel.

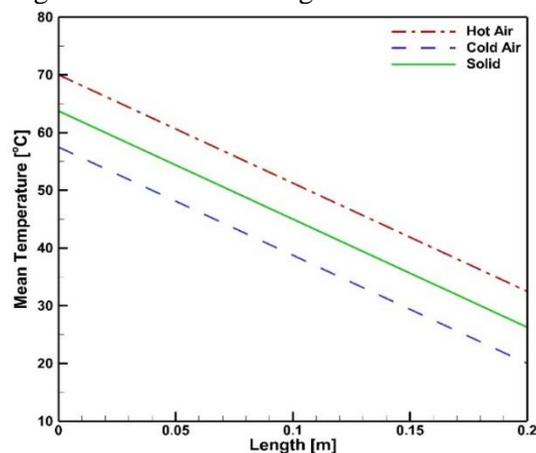
**Table 2.**The characteristics of the wheel and the heat wheel operating conditions.

Type	Value
Channel height (mm)	2
Channel width (mm)	3.8
Channel hydraulic diameter (mm)	1.6
Porosity	0.91
Rotor diameter (mm)	600
Shaft diameter (mm)	60
Rotor height (mm)	200
Purge Sector	None
Heatwheel material	Aluminium
Density (kg/m <sup>3</sup> )	2700
Specific heat capacity (J/kg·K)	900
Thermal conductivity (W/m·K)	220
Matrix angular velocity (rpm)	0-25
Air-flow rate (cfm)	100-1800
Inlet air temperature (°C)	20-100



**Figure 11.** Temperature distributions for the air and the wall at middle of the wheel

Figure 11 displays the variation of the air and matrix temperature in the middle of the wheel for both the cold and hot periods at the steady-state. The variation of the air temperatures is almost linear for both air streams with the rotation angle. As the wheel rotates during the hot period, the air temperature rises. And when the wheel rotates at the cold period the air temperature reduces. The variation of the matrix temperature starts from the lowest wall temperature and is increased to a point where the wheel is shifted to the cold period then the matrix temperature is decreased. During the steady-state operation, the matrix temperature at the finish of the warm period must be equal to the matrix temperature at the start of the cold period. Figure 12 shows the mean temperature for hot air, cold air and matrix versus wheel width at steady state. In the rotary heat exchanger, the warm air-flow is opposite the direction of the cold air-flow therefore that the warm air exit face is the face of the cold fluid entry and vice versa. With this type of flow, the temperature variance among the warm and cold streams is almost constant along with the heat exchanger. The matrix represents the medium of energy transfer between the warm and cold air and therefore it possesses medium temperature among the warm and cold air streams along with the heat exchanger.

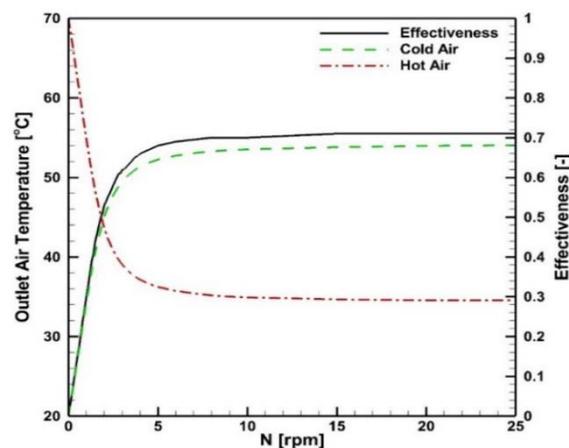


**Figure 12.** The mean temperature for the air and the wall along the wheel

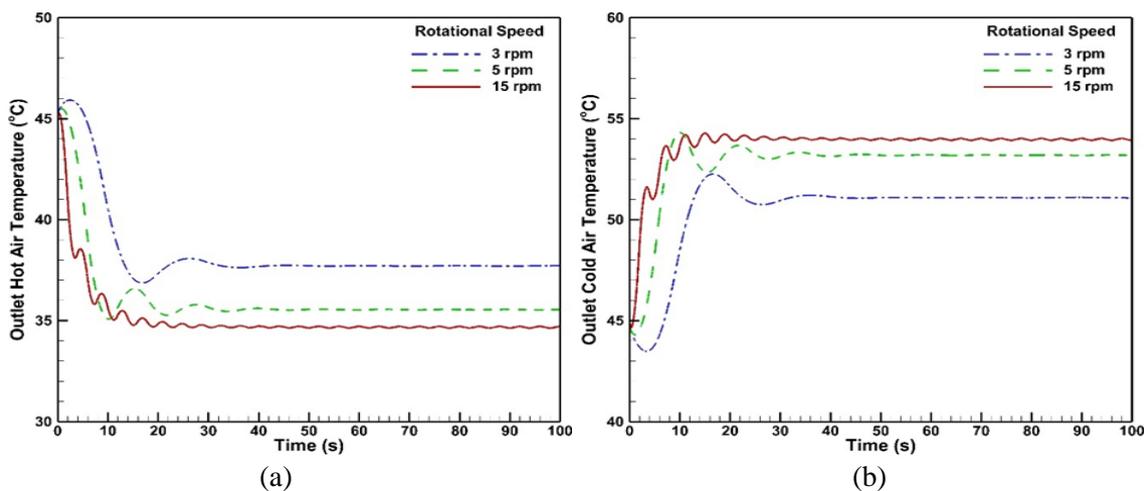
### 3.1 The influence of rotational velocity on the Rotary heat exchanger

The wheel rotational velocity is a significant parameter on the heat wheel effectiveness. Figure 13 displays the effect of the rotational speed of the wheel on outlet air temperatures from the wheel and the effectiveness. As seen, the effectiveness of the heat wheel is greatly increased by increasing the wheel rotational speed until a specific value then, no important change was realized in the effectiveness. By rising the rotational velocity, the exit cold air temperature is raised while the exit hot air temperature is reduced. The trend of the exit air temperature is like that of the heat exchanger effectiveness. As displayed, after 6 rpm the change among temperatures is nearly fixed which is like the effectiveness curve. Increasing the rotation speed of the wheel from zero to 6 rpm led to increasing

heat exchanger effectiveness from zero to 0.7. Rising the rotational speed due to increase heat transfer area available for energy transfer among hot and cold air which due to the rise in the heat exchanger effectiveness. Instead, it reduces the highest temperature of the wheel when it is in the warm period and rises the lowest temperature of the wheel when it is in the cold period because of the decrease in the time required for heat transfer between the wheel and air which lead to a decrease in the heat exchanger effectiveness. The equilibrium among these two reverse effects limits the movement of heat exchanger effectiveness curve. Three different values for wheel rotational speed are given as 3, 5 and 15 rpm, respectively (All-wheel channels have the same temperature at the beginning of rotation). Hot air temperature variations and cold air temperature differences from startup until the steady-state for various wheel rotational speed are shown in figure 14. Periodical fluctuation variations are shown in the hot and cold air temperatures as the wheel is periodic between the cold air and hot air. Additionally, extreme temperature variations among the wheel and the air have the lowest value in the high-speed case whereas they are higher in the small-speed case. The higher speed indicates that the wheel will have a lesser exposure time to either one of the warm and cold periods. Therefore, the average temperature variance among the matrix and the air remains bigger than those for the cases with lower speeds. Sustaining a high difference in temperature (between the air and the matrix) through alternating between hot air and cold air results in better heat transfer performance. Therefore, the steady-state is gotten quicker. Transient outlet air temperature variations from the beginning of the raising in rotational speed until the steady-state conditions for the rotational speeds are presented in figure 15. At the beginning the wheel isn't moving, the hot air passes in one half of the wheel and the cold air passes in the other half. Thus, one half of the wheel has the hot air temperature and the other half has the cold air temperature. When the wheel rotates the hot half of the wheel moves to the cold air area, which raises the air temperature fast, then the cold half of the wheel returns to the cold air area, which decreases the air temperature. Thus, causing frequency temperature between high value and low value. When the wheel rotates at low speeds, the time that the hot half of the wheel stays in the cold area increases, which reduces its temperature and at the same time the cold half temperature of the wheel increases, which reduces the frequency process between high and low-temperature values for the air.



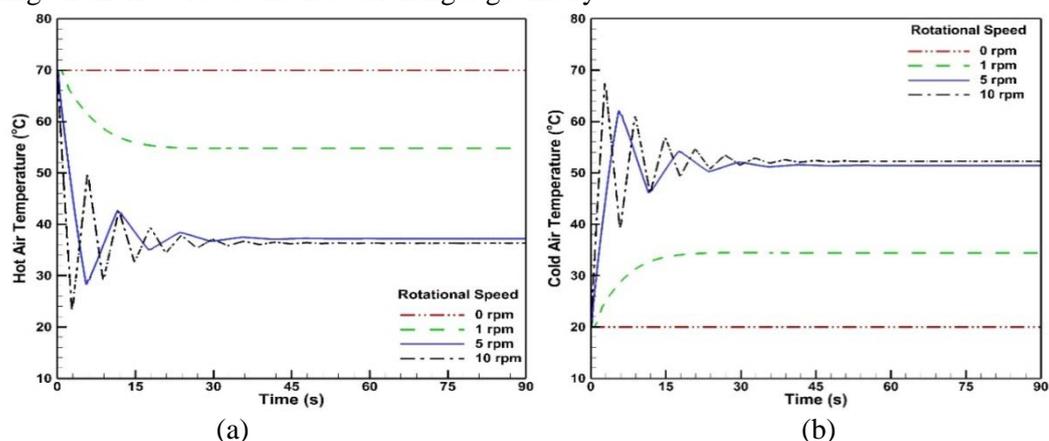
**Figure 13.**influence of rotational velocity on the effectiveness and exit air temperatures .



**Figure 14.** Influence of rotational velocity on exit air temperatures.

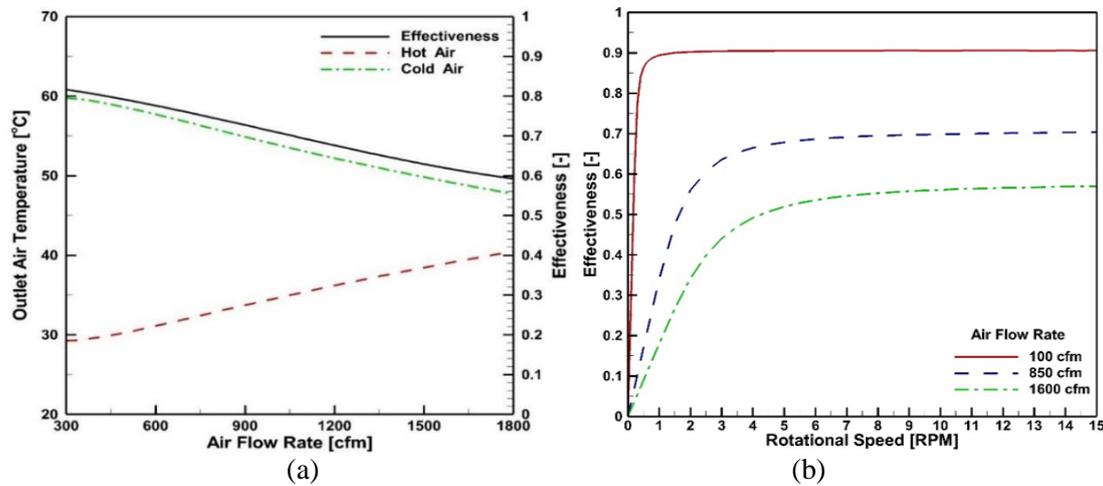
### 3.2 The influence of air-flow rate on the heat wheel

The performance of the heat wheel is influenced by the amount of flow air. The increase in air-flow rate (from 300 to 1800 cfm) led to a decrease in the effectiveness of the heat wheel (from 0.82 to 0.59). The effectiveness of the rotary heat exchanger was decreased due to the inability of the wheel to transfer all the energy that increased as a result of increased flow. Figure 16 (a) shows the influence of the air-flow rate on the effectiveness and exit air temperatures and figure 16 (b) shows the influence of the rotational velocity of the wheel on the effectiveness of heat wheel to three different values for air-flow rate 100, 850 and 1600 cfm, respectively. Therefore, at the lowest flow rate of the air stream (100 cfm), the greatest value of heat exchanger effectiveness happened and with rising the flow rate of the air stream, the heat exchanger effectiveness reduced. This was caused by the longer residence time of the air in the heat wheel for low flow rates but short residence time of the air for high flow rates. the effectiveness of the heat wheel is increased by increasing the wheel rotational speed until specific value and after that, no important change is realized in the effectiveness. But, the increase in the rotational speed led to an increase in the energy consumption, in addition to increasing the leakage rate between the two fluids, the effect of carryover, which leads to the contamination of the supply fluid. It is clear from the above that the less rotation speed leads to reduce operating expenses and reduce the mixing rate between the two fluids but increase the rotation speed leads to increase the efficiency of the heat exchanger until specific value and after that, no important variation is realized in the efficiency and prefer to work at that speed to achieve the highest performance rate with the lowest operating expenses and the lowest leakage rate between the two fluids. The optimal rotational speed is depending on air-flow rates and heat exchanger geometry.



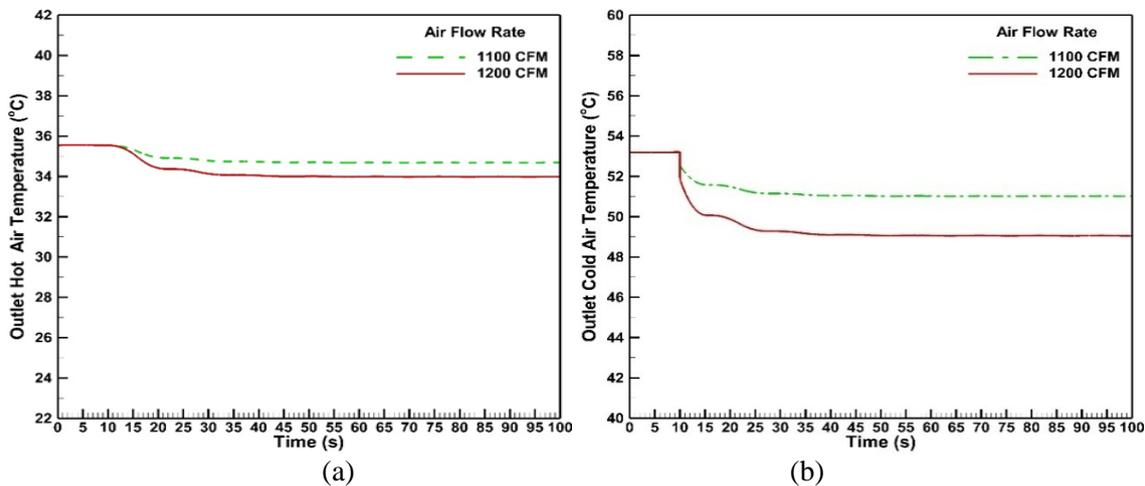
**Figure 15.** Outlet Air Temperature Versus Time with a Step Increase to rotational speed.

As seen in figure 16 (b), the optimal rotational speed is increased (from 1.8 to 7 rpm) by increasing the air-flow rate (from 100 to 1600 cfm).

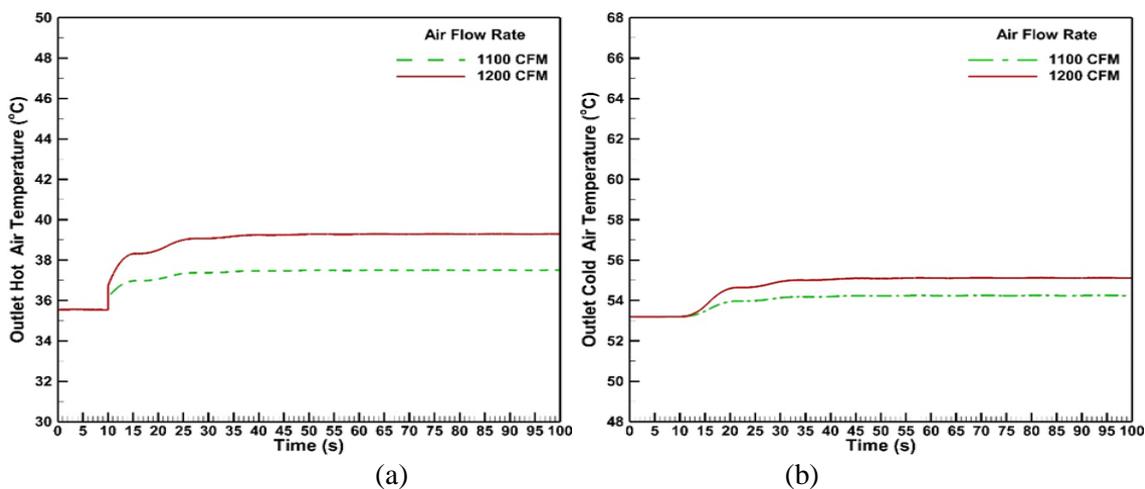


**Figure 16.** Influence of air-flow rate on the effectiveness and exit air temperatures.

Transient exit air temperature variations from the start-up of the increase in air-flow rate until the steady-state conditions for various air-flow rates are displayed in figure 17 (a, b) outlet air temperature versus time with a step increase to flow for cold fluid and figure 18 (a, b) outlet air temperature versus time with a step increase to flow for hot fluid). The hot and cold air outlet temperatures observed small periodical variations that match with the rotary heat exchange periodic variations as the heat wheel is periodic among the cold period and hot period. Increasing the flow rate of hot fluid leads to arise in the temperature of the hot air more than the rise of cold air temperature, because when the fluid flow rate increases, the effectiveness of the heat exchanger decreases. Therefore, the heat wheel is less able to transfer heat from hot air to cold air.



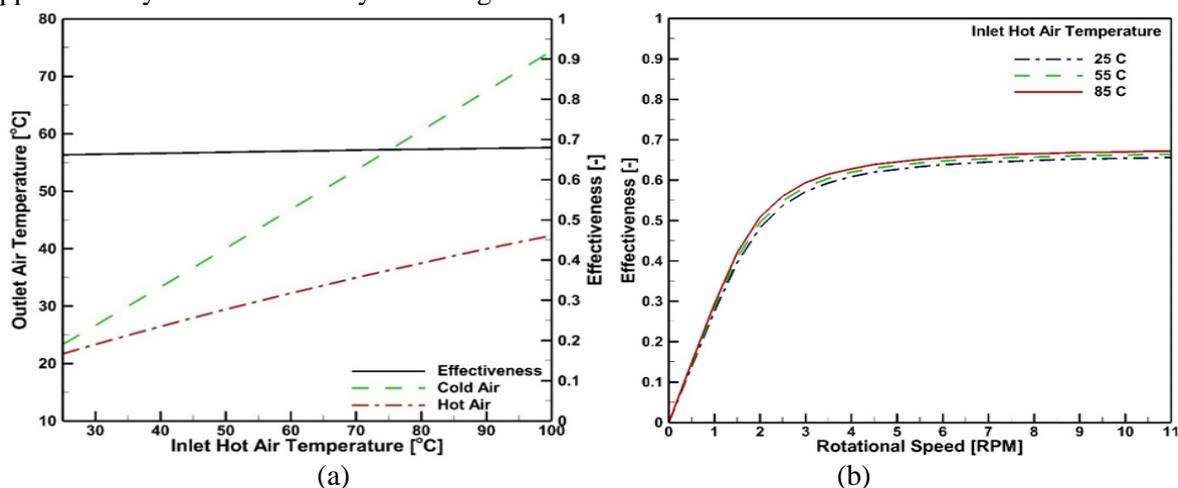
**Figure 17.** Outlet air temperature versus time with a step increase to flow for cold fluid.



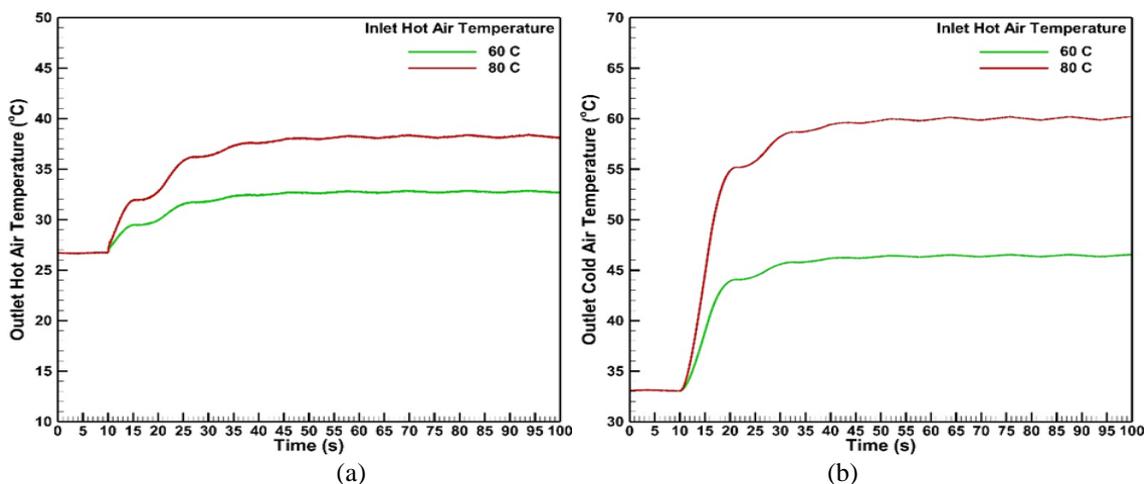
**Figure 18.** Outlet air temperature versus time with a step increase to flow for hot fluid.

### 3.3 The influence of inlet air temperature on the performance of the Rotary heat exchanger

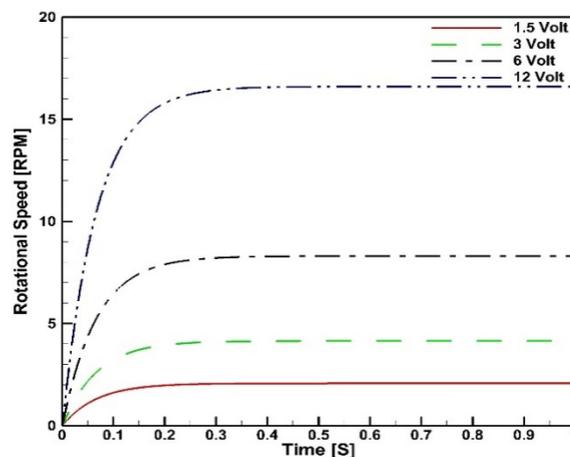
Figure 19 (a) shows the change of exit air temperature and the effectiveness with inlet hot air temperature, the effectiveness of the heat exchanger has a slight increase due to increase inlet air temperature. The small change in the rotary heat exchanger effectiveness causes by the change of the air properties with temperature. The specific heat capacity of the air at 1 bar changes from 1.006 kJ/kg K at 0°C to 1.012 kJ/kg K at 100°C, and the density of the air at 1 bar changes from 1.2942 kg/m<sup>3</sup> at 0°C to 0.9464 kg/m<sup>3</sup> at 100°C [17]. Figure 19 (b) shows the influence of the rotational velocity of the wheel on the effectiveness of the heat wheel matrix to three different values for inlet hot air temperature 25, 55 and 85°C, respectively. As seen, the optimal rotational speed is slightly decreased by increasing the inlet hot air temperature (the optimal rotational speed is unchanged approximation with air temperature about 6 rpm). The effect of outlet air temperature variation in inlet hot air temperature is displayed in figure 20. There are periodic changes seen in hot and cold air exit temperatures because of the fluctuating among the hot air and cold air. The effectiveness of the heat wheel is around 0.7 and it is approximately uniform for an extremely wide variety of temperatures. Therefore, when the temperature of the inlet hot air rises, most of the energy is transferred to the cold air and the increase of the cold air temperature is higher than the increase of the hot air temperature. The results presented that by rising the inlet hot gas temperature, the temperature of the exit cold air grew 2.2 times more than the temperature rise of the exit hot air. Steady-state conditions are achieved approximately with the similarly time range for all states.



**Figure. 19.** Influence of inlet gas temperature on the effectiveness of the rotary heat exchanger.



**Figure. 20.**Outlet air temperature versus time with a step increase to inlet hot air temperature.



**Figure. 21.**Wheel rotational speed versus time with a step increase in the inlet voltage supply

### 3.4 Control outlet air temperature of the heat exchanger system

Controlling the performance of heat exchangers can be used to prevent overheating or overcooling of the supply air during part-load operating conditions of HVAC systems. Numerical investigations are implemented to control the energy transfer rates in the rotary heat exchanger by using wheel speed control. Variable speed DC electric motor was used to drive the heat wheel. The wheel rotational speed variations for different supply voltage (1.5, 3, 6 and 12 V) are shown in figure 21. In the time domain, requirements for a control system are stated in terms of the standard quantities on the settling time, rise time, peak time, overshoot, steady-state error, and overshoot of a step response. The parameters of the PI controller adjusted repeatedly through computer simulations until the closed-loop system behaviour as desired. Setpoint tracking and disturbance rejection of the feedback controller is shown in figure 22. The feedback PI controller shows 24.24% of overshoot and 11.5 seconds of settling time.

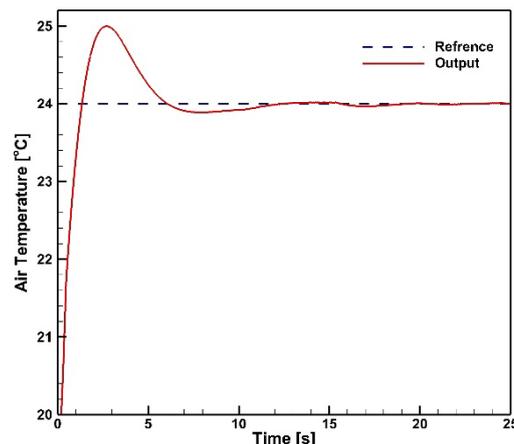


Figure 22. Output air temperature response using PI controller.

#### 4. Conclusion

- The developed heat transfer model could predict the effectiveness of the heat wheel, the exit air temperature from the heat wheel and the optimum rotating velocity of the wheel for certain operating conditions.
- Accurate agreement among simulations and the published experimental data is accomplished within an acceptable margin of error (the greatest error is always smaller than 5%).
- The effectiveness of the rotary heat exchanger is greatly increased by growing the wheel rotational speed until a specific value and after that, no big change was achieved in the effectiveness. Growing the rotation speed of the wheel from zero to 6 rpm led to increasing heat exchanger effectiveness from zero to 0.7. The response of the outlet air temperature is like that of the heat exchanger effectiveness.
- Periodical fluctuation variations are shown in the hot and cold air temperatures while the wheel is a rotation between the cold airstream and hot airstream. Also, extreme temperature variations between the wheel matrix and the air have the lowest amount in the high-speed state as they are greater in the low-speed state.
- The increase in air-flow rate (from 300 to 1800 cfm) led to a decrease in the effectiveness of the heat wheel (from 0.82 to 0.59).
- The optimal rotational speed is depending on air-flow rates and heat exchanger geometry. The optimal rotational speed is increased (from 1.8 to 7 rpm) by increasing the air-flow rate (from 100 to 1600 cfm).
- The effectiveness of the heat wheel is very nearly constant for a very large variety of temperatures.
- The optimal rotational speed is unchanged approximation with air temperature.
- The search proved that by rising the inlet hot air temperature, the temperature of the outlet cold air rise 2.2 times more than the exit hot air temperature for balanced air-flow.
- Controlling the performance of heat exchangers can be used to prevent overheating or overcooling of the supply air during part-load operating conditions of HVAC systems.
- Integrating the RHE with PI controller to achieve the required supply air temperature by modifying the rotating speed. The feedback PI controller shows 24.24% of overshoot and only 11.5 seconds to settling.

#### Nomenclature

A	Cross-section area for any channel, m <sup>2</sup>
B	Friction coefficient, Nm s/rad
C <sub>m</sub>	Specific heat constant of the matrix, J/kg K
C <sub>p</sub>	Specific heat constant, J/kg K

$D_h$	Hydraulic channel diameter, m
$D_z$	Length of one part, m
$G_z$	Greatz number
$h_{HT}$	Convection coefficient, $W/m^2 K$
$i_a$	Armature current, A
$J$	Moment of inertia, $kg m^2$
$K$	Conduction coefficient, $W/mK$
$K_e$	back emf constant, $V rad/s$
$K_i$	Motor torque constant, $Nm/A$
$L$	The thickness of the wheel, m
$L_m$	armature inductance, $mH$
$Nu$	Nusselt number
$P$	channel perimeter, m
$Pr$	Prandtl number
$R$	armature resistance, $\Omega$
$Re$	Reynolds number
$T$	Temperature of air, $K$
$t$	Time, s
$U_g$	The speed of air within the channel, $m/s$
$V$	Voltage, $V$
$v_f$	face air velocity, $m/s$
Greek symbols	
$\mu$	Viscosity of air, $N.s/m^2$
$\varepsilon$	Effectiveness
$\rho$	Density of air, $kg/m^3$
$\Sigma$	wheel porosity
$T$	Torque, $Nm$
$\Phi$	Angle between Discretization channel, $rad$
$\Omega$	Angular velocity, $rad/s$
Subscripts	
A	armature
B	back
C	Cold
F	forward segment
FD	Fully developed
G	gas
H	hot
In	Inlet
L	Load
M	Motor
M	Channel Material
Out	Outlet
P	previous segment
Abbreviation	
RHE	Rotary heat exchanger
PI	A proportional–integral controller

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