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Research Article

Numerical Investigation of Fin Number, Fin Spacing, and Air Velocity Effects on the Thermal Performance of Rotary Regenerative Heat Exchangers

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ABSTRACT

This study presents a detailed numerical investigation into the thermal performance of rotary regenerative heat exchangers, focusing on the influence of fin number, fin-to-inner-diameter spacing, and air inlet velocity. A simplified annular cross-sectional model was utilized to reduce computational cost while preserving geometric accuracy. A total of nine model variations were created by parametrically altering the number of fins (11, 13, and 15) and fin spacing (0.5 mm, 0.75 mm, and 1 mm). Simulations were performed using under transient flow conditions, with air velocities ranging from 2.6 m/s to 3.8 m/s. Results showed that increasing the number of fins and expanding fin spacing both enhance heat transfer by improving flow uniformity and turbulence levels, with effectiveness improvements reaching up to 11%. Conversely, higher air velocities reduce heat exchanger effectiveness due to shortened contact time and boundary layer disruption. The findings highlight that even within a geometrically limited segment, measurable changes in performance occur, offering valuable insights for system-level design optimizations. The study contributes to the literature by demonstrating the feasibility of high-fidelity modeling of small-scale segments to evaluate parameter sensitivity in rotary heat exchangers.

Introduction

Energy plays a critical role in numerous areas today, ranging from industrial processes to everyday life. Considering the growing demand for energy and the limited availability of fossil fuel resources, the efficient use of energy has become increasingly important. In this context, the reduction or recovery of waste heat emerges as a fundamental component of sustainable energy management. Waste heat recovery systems are employed in a wide range of applications from industrial facilities to HVAC systems to conserve energy, reduce operating costs, and minimize environmental impact. Therefore, heat recovery technologies such as regenerative heat exchangers are among the most effective solutions for efficiently utilizing waste heat.

Rotary regenerative heat exchangers are an innovative type of heat exchanger that enhance the energy efficiency of systems by recovering thermal energy. They have a wide range of applications, including HVAC systems, industrial heating processes, gas turbines, waste heat recovery systems, and aerospace applications. These systems reduce energy consumption and operating costs by transferring heat from the exhaust fluid to the fresh fluid through heat transfer surfaces. They play a significant role in increasing thermal efficiency and promoting sustainable energy management. Studies on regenerative heat exchangers are generally categorized into three groups: analytical, numerical, and experimental. Some studies within this scope are outlined below.

Rotary regenerative heat exchangers achieve higher efficiency compared to stationary (non-rotating) systems by distributing temperature differences more evenly through rotational motion. Numerical studies conducted by Çiftçi and Sözen have demonstrated the effectiveness of rotary heat exchangers. In their study, they compared the system performance at an optimal rotational speed with a non-rotating case and found that the effectiveness increased by approximately 20% due to the rotational motion. Furthermore, their research indicated that the use of silica gel significantly enhanced the rate of heat transfer [1].

The fin material used in regenerative heat exchangers has a significant impact on the system's heat transfer efficiency, durability, and overall energy recovery performance. Yadav et al. [2] investigated the performance of various materials used in rotary fin wheels. They recommended the use of composite silica gel–LiCl and composite silica gel–$CaCl_2$ materials in air conditioning applications due to their favorable energy consumption characteristics. Intini et al. [3] experimentally examined the performance of AQSOA zeolite-based materials in rotary heat exchangers. Their experiments, conducted under various temperature and humidity conditions, yielded empirical correlations, indicating that this innovative material is suitable for applications at medium to high temperatures (80°C and 100°C). A. Al-Alili et al. [4] conducted experimental investigations on the performance of a new zeolite-based material called FAM-Z01. They found that as air temperature and relative humidity increased, the material's moisture adsorption capacity also improved. Their findings revealed that the developed material could be effectively used at low temperatures in terms of energy efficiency, with optimal performance observed at rotor speeds of 20–30 RPH. Goldsworthy and White [5] studied the design and performance of rotary heat exchangers and developed a novel design incorporating an integrated cooling system to enhance the dehumidification capacity of adiabatic wheels. Their analysis showed that silica gel materials had higher moisture adsorption capacity compared to polymer-based alternatives. Although replacing aluminum with PVC reduced manufacturing costs, it also decreased system performance due to PVC's lower thermal conductivity. As a result of the design modifications, a moisture removal capacity increase of up to 40% was achieved, demonstrating the system's potential for improved energy efficiency. Zhang et al. [6] evaluated the performance of ten different materials in rotary heat exchangers: silica gel B, silica gel 3A, silica gel RD, silica gel/LiCl, silica gel/$CaCl_2$, zeolite 5A, zeolite 13X, zeolite 13X/$CaCl_2$, $CaCl_2$, and LiCl. The best-performing materials at low temperatures (40–60°C) were silica gel 3A, silica gel RD, and silica gel B; whereas at higher temperatures (60–90°C), the top-performing materials were silica gel/LiCl, silica gel/$CaCl_2$, and zeolite 13X.

On the other hand, research focusing on the parameters that enhance thermal efficiency in regenerative heat exchangers has also gained considerable attention. Özdemir and Serincan analyzed performance based on rotational speed, inlet fluid temperature, and load conditions. They emphasized the need to determine low inlet temperatures and optimal angular velocities in order to increase energy efficiency and prevent condensation/corrosion [7]. Heidari-Kaydan and Hajidavalloo [8] conducted a three-dimensional thermal simulation of a rotary-type preheater in a steam power plant. The preheater's performance was evaluated in terms of parameters such as rotational speed, mass flow rate, separator plate material, and inlet air temperature. Simulation results showed that rotational speed and flow rate significantly affected preheater performance. However, changes in material and increases in inlet air temperature did not produce notable differences in efficiency. Tu et al. [9] studied the performance of rotary heat exchangers used for enthalpy recovery and dehumidification. Using an experimentally validated mathematical model, they examined the effects of various rotational speeds, materials, and air mixing parameters on performance. Their findings highlighted the importance of selecting appropriate substrate materials and rotational speeds for both moisture recovery and heat recovery wheels. Men et al. [10] conducted both experimental and numerical studies to investigate the effects of different operating conditions on thermal performance. They observed that condensation could occur under high temperature and humidity conditions, potentially influencing system performance and warranting further investigation. As the cold air inlet temperature decreased from –16°C to –24°C, the condensation rate increased from 13.5% to 19.8%, while the total heat recovery efficiency remained steady at around 70%. When the rotational speed of the rotary heat exchanger was increased from 5 rpm to 12 rpm, total thermal efficiency rose from 75.5% to 84.0%, and moisture recovery efficiency increased from 36.4% to 39.7%, with the condensation rate varying between approximately 15% and 17%.

Men et al. [11] compared the performance of a rotary heat exchanger in terms of both heat and moisture recovery with other technologies for the recovery of industrial waste flue gas. Under experimental conditions, the rotary heat exchanger achieved a total thermal efficiency of 88.4%, whereas the alternative technological design reached only 60.0%. Accordingly, the overall system recovery efficiency was measured at 93.8% for the rotary heat exchanger and 81.8% for the other design. These results indicate that rotary heat exchangers are highly effective in waste heat recovery systems, particularly in cases requiring high recovery rates within limited space constraints. Ruan et al. [12] conducted a performance analysis of rotary heat exchangers used in waste heat recovery systems, focusing on the effect of purge air. They found that the additional section used to reduce contaminant accumulation caused only a minimal decrease in performance. Design parameters such as rotor geometry, rotational speed, and purge air ratio were identified as having a direct impact on system performance.

Regenerative rotary heat exchangers are vital systems that enable energy savings through high heat recovery efficiency (60–80%) and low pressure drop. Numerical modeling techniques such as the Finite Difference Method (FDM), Finite Volume Method (FVM), and Finite Element Method (FEM) have been employed for analyzing heat transfer and fluid dynamics. Critical parameters that directly influence exchanger efficiency include rotational speed, geometric configuration, and fluid turbulence. The ε-NTU method is the most commonly used analytical technique for evaluating the performance of heat exchangers. Optimization studies and the use of genetic algorithms have shown that efficiencies of up to 85% can be achieved [13].

A comprehensive review has summarized both experimental and numerical developments in desiccant rotary heat exchanger systems, highlighting emerging materials and hybrid geometries [14]. A PhD study performed geometric optimization of heat storage plates inside rotary regenerative heaters using CFD and multi-objective optimization, confirming that fin geometry and element geometry significantly affect thermal performance. [15]. Zmrhal et al. experimentally and numerically investigated the sensible heat effectiveness of rotary regenerative heat exchangers at low rotational speeds (0–16 rpm), proposing a new ε–NTU correlation that accurately predicts performance across different wheel geometries and airflow rates [16].

Although numerous numerical and experimental studies have investigated the performance of rotary regenerative heat exchangers, most of them focus either on full-scale wheel geometries or on simplified one-dimensional analytical models. Such approaches generally lead to high computational costs or fail to resolve local fin-level heat transfer effects, which strongly influence overall thermal effectiveness. In a previous numerical study, the effect of fin number on the thermal performance of rotary regenerators was investigated under a fixed geometric configuration [19]. The fin spacing value adopted in that study was not employed in the present work, and different fin-to-inner-diameter spacing values were considered, resulting in a fundamentally different geometric configuration. Consequently, even for identical fin numbers, the thermal performance trends obtained in the present study differ from those reported previously. In particular, the combined impact of fin number, fin-to-inner-diameter spacing, and inlet air velocity on the segment-level temperature distribution and thermal effectiveness has not been thoroughly quantified in the literature. To address this gap, the present study develops a high-fidelity numerical model of a representative annular segment of a rotary regenerative heat exchanger. This approach significantly reduces simulation time while preserving geometric and physical fidelity, allowing the capture of localized flow and temperature fields that cannot be resolved in simplified models.

Material and Method

Geometry and Operating Parameters of the Rotary Regenerator

In this study, the performance of rotary heat exchangers was numerically analyzed by examining the effects of different fin counts, fin geometries, and inlet air velocities. The actual model has a length of 100 mm and a diameter of 300 mm. However, due to the geometric uniformity of all microchannel, the analysis was performed on a coaxial annular section to reduce computational cost. A simplified model geometry was created with a length of 100 mm and an inner diameter of 22 mm. The three-dimensional design of the model is shown in Figure 1. This approach allowed for a detailed and efficient evaluation of boundary layer dynamics as well as the impact of fin count on heat transfer.

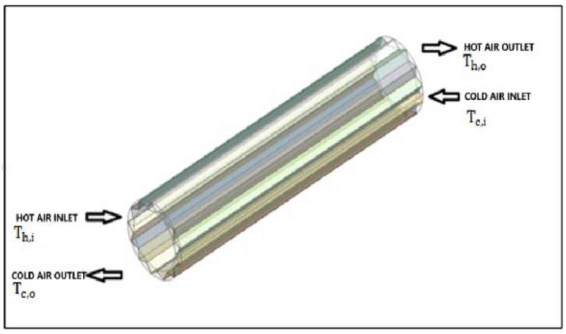


Figure 1. Three-dimensional view of the model

The geometric models were created using the ANSYS Design Modeler environment. During the modeling process, the outer geometry of the regenerator was first drawn, followed by the placement of parametrically defined fins at equal intervals. The number of fins (11, 13, and 15) and the distances between the fins and the inner diameter (0.5 mm, 0.75 mm, and 1 mm) were defined as variable parameters to create different variations. The models generated according to these parameters are presented in Table 1. Figure 2 illustrates the geometric parameters of the created models.

Table 1. Properties of model geometries

Models	Number of Fins	Distance Between Inner Diameter of Fins
Model 1	11 fins	0,5 mm
Model 2	13 fins	0,5 mm
Model 3	15 fins	0,5 mm
Model 4	11 fins	0,75 mm
Model 5	13 fins	0,75 mm
Model 6	15 fins	0,75 mm
Model 7	11 fins	1 mm
Model 8	13 fins	1 mm
Model 9	15 fins	1 mm

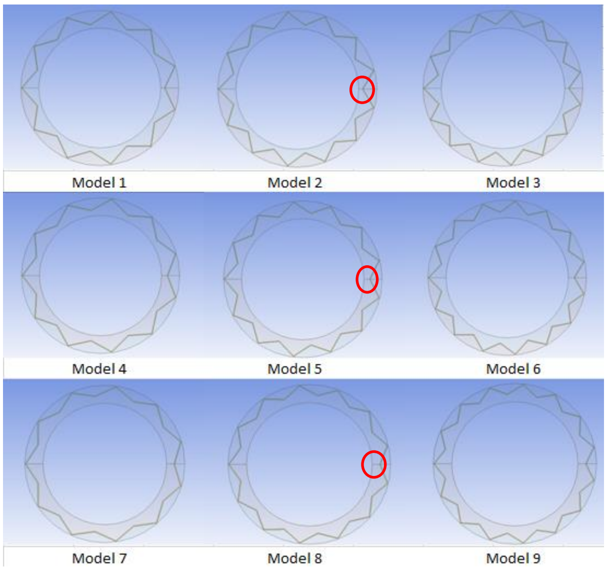
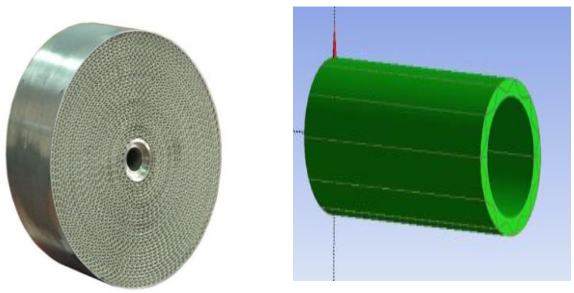


Figure 2. Representation of model geometries

Numerical Method

In the literature, numerical, theoretical, and experimental approaches exist to evaluate the thermal performance of rotary heat exchangers. However, due to the complex channel geometries, the applicability of theoretical models is limited, while experimental studies become costly and time-consuming when testing all configurations. To overcome these limitations, this study relies solely on numerical analysis. Instead of examining each channel individually, the model uses annular channels defined as a coaxial control volume to reduce computation time and resource consumption. This approach significantly shortens simulation time while enabling a detailed assessment of the effects of parameters such as the number of channels and air velocity on heat transfer. A comparison between the actual and simplified geometries is presented in Figure 3. The governing equations for continuity, momentum, and energy were formulated based on standard CFD theory [16,17].



a) Actual geometry b) Simplified geometry

Figure 3. Actual channel geometry and simplified channel geometry

Governing equations (fluid, incompressible, laminar)

Continuity Equation

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

Momentum (inertial frame)

$$\rho(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} \tag{2}$$

Momentum (MRF)

$$\rho\left(\frac{\partial \mathbf{u}_r}{\partial t} + \mathbf{u}_r \cdot \nabla \mathbf{u}_r\right) = -\nabla p_r + \mu \nabla^2 \mathbf{u}_r - 2\rho\, \boldsymbol{\Omega} \times \mathbf{u}_r - \rho\, \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) + \rho \mathbf{g} \tag{3}$$

In this expression, $\mathrm{u}_r$represents the velocity in the rotating reference frame, and $p_r$denotes the modified pressure; the second and third terms correspond to the Coriolis and centrifugal accelerations, respectively.

Energy

$$\rho c_p(\frac{\partial T_f}{\partial t} + \mathbf{u} \cdot \nabla T_f) = k_f \nabla^2 T_f \; + \; \Phi \tag{4}$$

In the equations, uand $\mathrm{u}_r$denote the velocity vectors in the inertial and rotating reference frames, respectively, while $p_r$represents the modified pressure including rotational effects. The symbols $T_f$and $T_s$refer to the temperatures of the fluid and solid domains, and k_f, k_s, c_p, and $c_{p,s}$indicate the thermal conductivities and specific heat capacities of the fluid and solid materials.

The effectiveness is defined purely on a thermal basis, following the conventional definition for sensible heat recovery in rotary regenerative heat exchangers. It is calculated using the temperature difference between the inlet and outlet flows. The equation is given in Eq.5.

$$\varepsilon = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} \tag{5}$$

$T_{c,in}$and $T_{c,out}$are the inlet and outlet temperatures of the cold air stream, and $T_{h,in}$is the inlet temperature of the hot air stream.

In the numerical analyses, pressure-based, transient, and natural convection effects were considered by enabling gravity and energy options to accurately calculate heat transfer. The properties of aluminum, selected as the material, were obtained from the ANSYS library. The rotational speed of the rotary heat exchanger was assumed constant at 10 revolutions per minute (rpm). Boundary conditions for the fluids were set as constant inlet temperatures (308.15 K for the hot side and 297.15 K for the cold side) and adiabatic outer walls are now specified. The outlet boundary is set to atmospheric pressure, and a non-slip condition is imposed on all solid surfaces. The rotational motion of the matrix is now explicitly defined as a Multiple Reference Frame (MRF) region rotating at 10 rpm, consistent with our previously validated configuration. The chosen temperature and velocity boundaries correspond to realistic operating conditions for low-speed regenerative heat exchangers. The general solver settings selected for the simulations are provided in Table 2. The numerical simulations were carried out using ANSYS Fluent. The PRESTO! scheme was employed for pressure interpolation to improve the accuracy of pressure calculation, especially for complex geometries. The COUPLED algorithm was selected for pressure–velocity coupling together with the laminar flow model, allowing the continuity and momentum equations to be solved simultaneously. The governing equations considered in the simulations include the continuity, momentum (Navier–Stokes), and energy equations. For spatial discretization, the Second Order Upwind scheme was applied to the momentum and energy equations to achieve higher numerical accuracy. The laminar flow model was selected based on the Reynolds number calculation. Using the thermophysical properties of air at 308 K $\left(\rho = 1.14\,\mathrm{kg/m^3}, \mu = 1.9 \times 10^{-5}\,\mathrm{Pa.s}\right)$, inlet velocity $(V = 3\,\mathrm{m/s})$, and hydraulic diameter $(D_h = 0.005\,\mathrm{m})$, the Reynolds number was calculated as approximately 1140. Since this value is lower than 2300, the flow was assumed to be laminar.

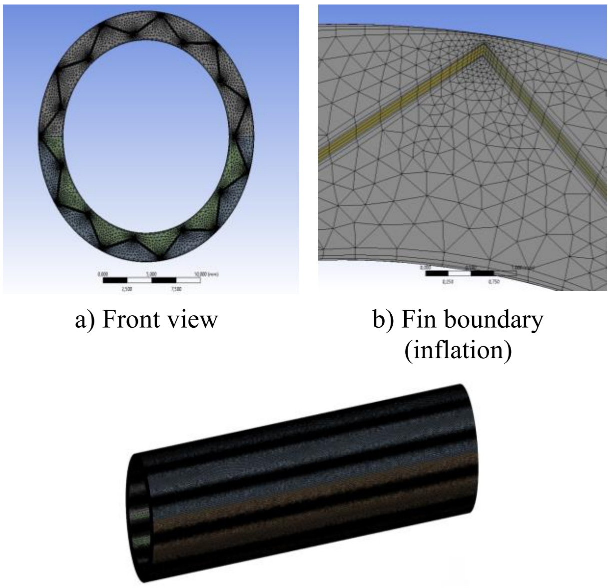
Table 2. General settings for the solution

Model	Laminer flow
Solver Method	Coupled
Pressure discretization	Presto
Energy and Momentum discretization	Second Order Upwind
Maximum Iterations per time step	1000

For the meshing of the examined models, the "body of influence" approach was employed to increase the mesh density in geometrically narrow regions, while the "inflation" layer was applied to enhance the boundary layer resolution near wall surfaces. Mesh independence studies ensure the reliability of numerical analyses by minimizing the influence of cell size and density on the results. In this context, meshes with varying resolution levels were compared, and an optimal mesh size was determined based on the consistency–effectiveness relationship. Quantitative indicators of mesh quality, such as skewness and orthogonal quality, were evaluated. A skewness value close to zero indicates that the cells are near an ideal geometric shape, while an orthogonal quality value approaching one signifies a good alignment between the face normal and the vector connecting the cell centers, reflecting a high-quality mesh structure. Using these methods, the generated mesh was optimized to accurately capture boundary layer dynamics while maintaining computational efficiency. The results of the mesh quality and mesh independence study are presented in Table 3. Screenshots of the mesh structure are shown in Figure 4. Since the simulations were performed under transient conditions, the value of 1000 iterations represents the maximum number of iterations allowed per time step to ensure convergence stability.

Table 3. Independence from mesh structure and quality results

Nodes	Elements	Cells	Element quality	Skewness	Orthogonal quality	Cold flow outlet temperature
7981624	24768161	9428538	0,621	0,242	0,757	304,46
15398743	51998191	17445334	0,664	0,233	0,768	304,52
31198916	124921133	33762360	0,732	0,223	0,777	304,56



a) Front view

b) Fin boundary (inflation)

c) General view

Figure 4. Mesh structure images

To verify the mesh independence of the obtained results, a series of simulations were conducted using meshes with varying cell counts. As shown in Table 3, the variations in cold air outlet temperatures were negligible. On the other hand, increasing the number of elements improved mesh quality but led to a significant increase in computation time. Considering this trade-off, the final analyses were performed using a mesh structure containing 7,981,624 nodes. Additionally, to ensure iteration independence of the results, further analyses were carried out with different iteration counts, and it was observed that the solution results stabilized after 1,500 iterations.

The numerical model employed in this study was previously validated in our earlier work [19], by comparing the thermal effectiveness values of a rotary regenerative heat exchanger at rotational speeds of 0 rpm and 10 rpm. The results showed good agreement, with deviations ranging between 1.69 % and 5.49 % compared to the reference study, respectively. Since the same geometry with different size, boundary conditions, and solver settings are employed in this study, only a brief summary of the validation is presented here, with full details available in the referenced publication.

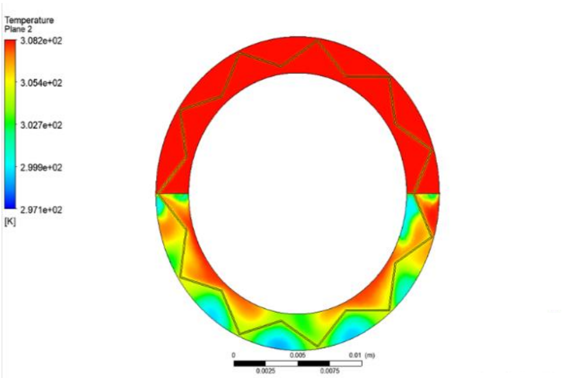
The present study is a purely numerical investigation aimed at evaluating the relative influence of geometric parameters on the thermal behavior of a rotary regenerative heat exchanger. Therefore, the numerical results are not intended to reproduce exact real-system values with absolute accuracy. Instead, a simplified model is deliberately employed to isolate the effects of fin number, fin spacing, and air inlet velocity under consistent numerical conditions. Although the absolute numerical values may differ from those of a full-scale industrial system, the observed trends remain physically meaningful and provide valuable insight into parameter sensitivity.

Results and Discussion

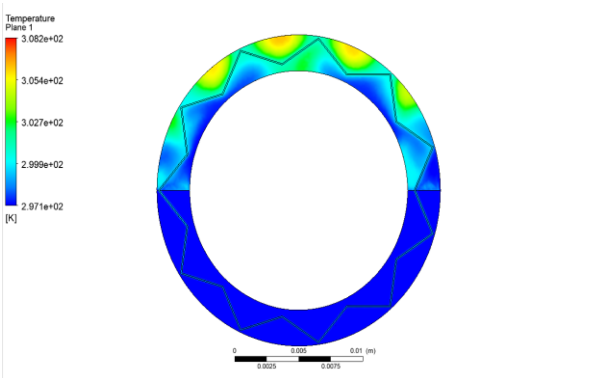
Rotary regenerative heat exchangers are receiving increasing attention in both industrial processes and HVAC applications due to their high heat recovery rates and compact structures. In this study, the thermal performance of a regenerative heat exchanger made of aluminum, with an inner diameter of 17 mm, an outer diameter of 22 mm, and a length of 100 mm, was investigated. In the analyses, the inlet temperatures of the cold and hot air streams were set at 297.15 K and 308.15 K, respectively, in accordance with similar studies in the literature. Air inlet velocities were tested at three different values ranging between 2.6 m/s and 3.8 m/s. While the rotational speed one of the critical parameters affecting the system’s dynamic behavior was kept constant at 10 revolutions per minute (rpm), the thermal efficiency of nine different geometric models, formed by combinations of fin numbers (11, 13, 15) and fin-to-inner-diameter distances (0.5 mm, 0.75 mm, 1 mm), was compared. All analyses were conducted over 6-second intervals, corresponding to a full rotation period, and outlet temperatures were recorded to examine the effects of parameters on performance in detail. Comparisons were also made regarding the influence of air inlet velocity on systems with different fin counts and the effect of geometry variations on overall performance.

Effect of the Number of Fins on Performance

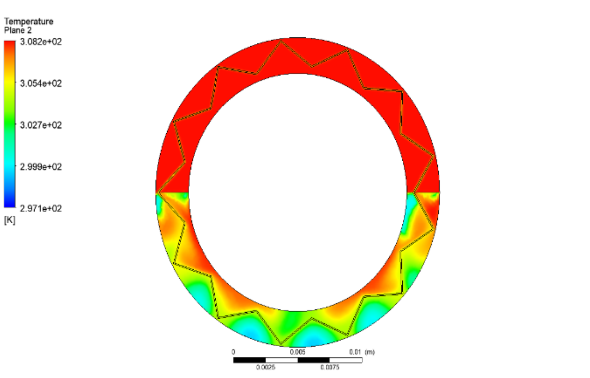
As seen in Figures 5a, 5b, and 5c, the temperature reaches its maximum at the inner wall and fin roots, while decreasing toward the fin tips, forming lower temperature regions. In contrast, Figures 5e, 5f, and 5g show that the temperature is at its minimum at the inner wall and fin roots, increasing toward the fin tips, thereby creating higher temperature regions. In cases with hot air inlet, heat transfer is more widespread and the temperature distribution on the fin surfaces is more homogeneous. On the other hand, in cold air inlet conditions, temperature changes are more localized, and gradients are noticeably sharper.



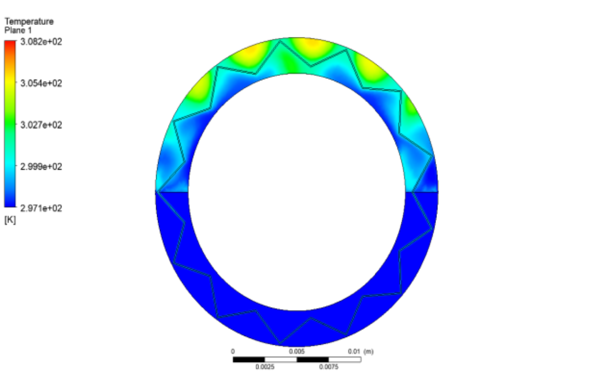
a) 11 fins hot inlet, cold outlet



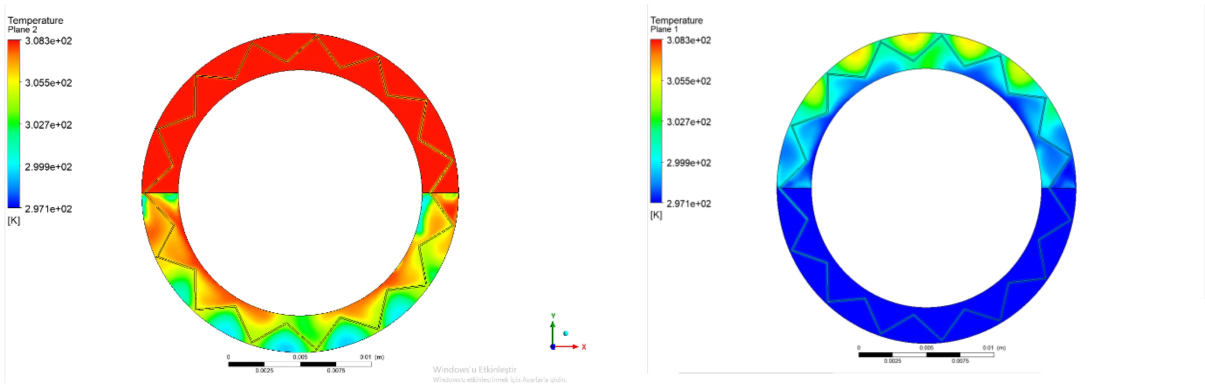
e) 11 fins cold inlet, hot outlet



b) 13 fins hot inlet, cold outlet



f) 13 fins cold inlet, hot outlet

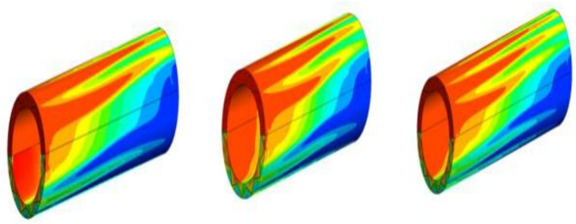


c) 15 fins hot inlet, cold outlet

g) 15 fins cold inlet, hot outlet

Figure 5. Effect of fin number on temperature distribution

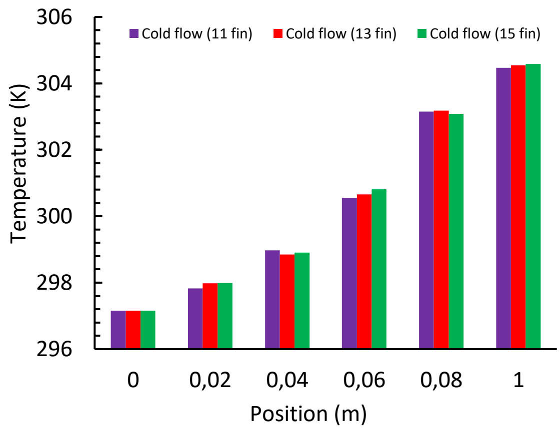
Isometric views of the models with different fin numbers are presented in Figure 6. As observed in the figure, in systems with hot fluid inlets and cold outlets, the temperature of the fluid decreases more rapidly as the number of fins increases. Furthermore, the increase in temperature gradient along the flow path indicates higher heat flux and, consequently, an improvement in the system's thermal performance.



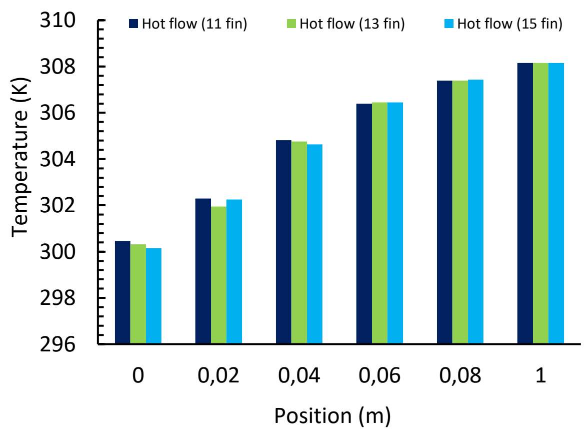
a. 11 fins b. 13 fins c. 15 fins

Figure 6. Temperature distribution for different fin numbers

Although there are variations in temperature distributions and regions based on the temperature contours, the temperature changes in different regions are presented more clearly in Figure 7. Figure 7a shows the temperature variation of the cold flow with respect to position and illustrates the effect of the fin count; as the number of fins increases, the temperature rises slightly. Figure 7b displays the temperature distribution of the hot flow and similarly shows that an increase in the number of fins causes a slight decrease in temperature values at the outlet (z = 0 m). In both flow types, temperature increases steadily as the position advances, and the impact of the fin count becomes more pronounced with flow progression. For both flows, the improvement in temperature values due to increased fin count occurs in the range of approximately 0.5% to 1%.



a) Cold flow (inlet at z=0)

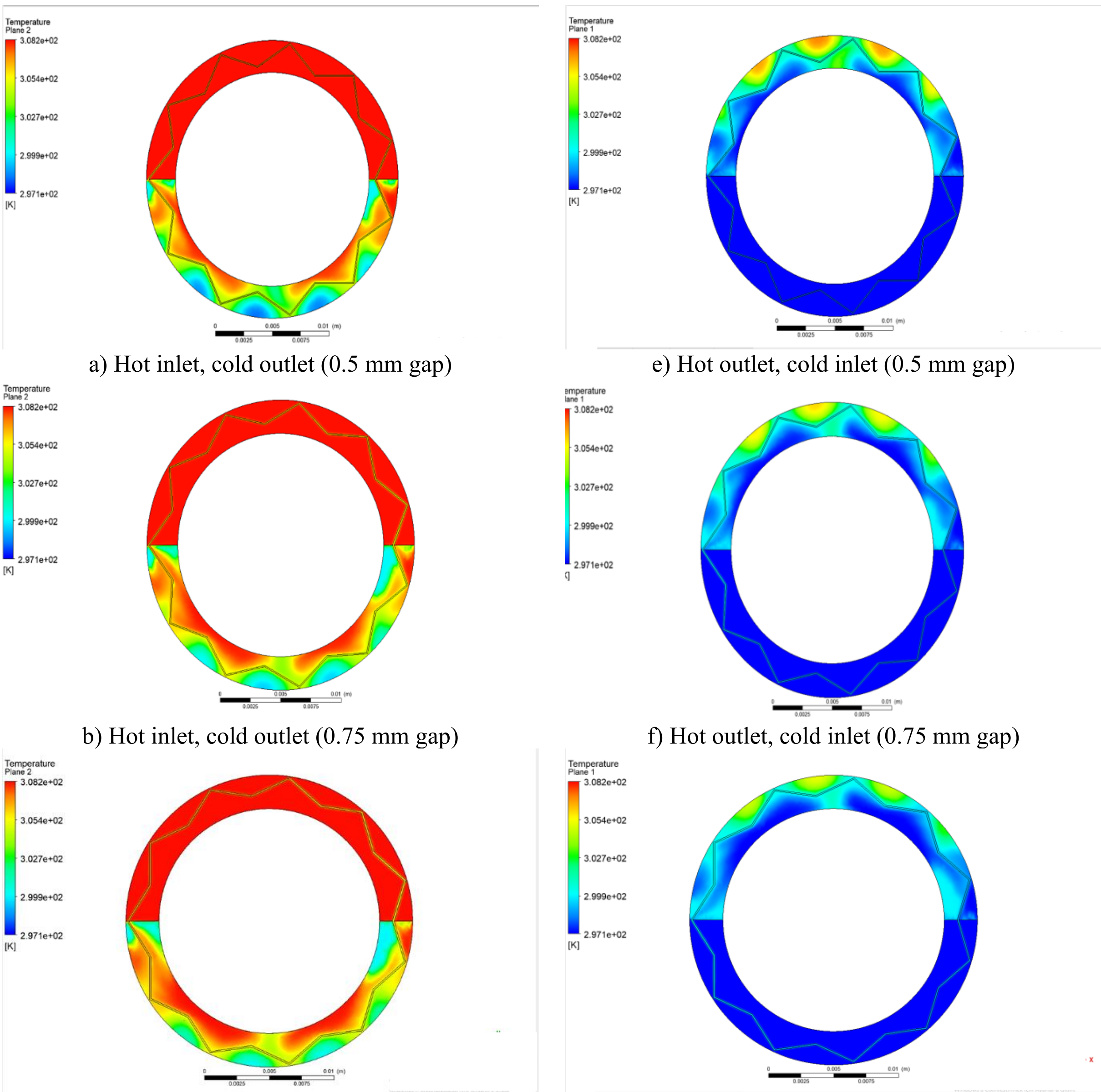


b) Hot flow (inlet at z=1)

Figure 7. Temperature variations of fluids in the z-direction

Effect of Fin Geometry on Performance

In this study, three different models were designed to investigate the effect of the geometric position of the fins relative to the inner diameter of the heat exchanger on performance. In each model, the distance of the fins from the inner diameter was varied parametrically at 0.5 mm, 0.75 mm, and 1 mm, and the differences in heat transfer characteristics were analyzed numerically. The main objective here is to examine how the placement distance of the fin geometry influences the thermal efficiency of rotary-type heat exchangers. Figure 8 presents the effect of the fin position (with 11 fins) relative to the inner diameter on temperature distribution. The temperature distribution is shown for both the cold and hot fluid outlet regions.



a) Hot inlet, cold outlet (0.5 mm gap)

e) Hot outlet, cold inlet (0.5 mm gap)

b) Hot inlet, cold outlet (0.75 mm gap)

f) Hot outlet, cold inlet (0.75 mm gap)

c) Hot inlet, cold outlet (1 mm gap)

g) Hot outlet, cold inlet (1 mm gap)

Figure 8. The effect of fin geometry on temperature distribution

Figure 9 presents the effect of fin spacing on effectiveness for different fin counts. In the model with a 0.5 mm spacing, effectiveness increased from 66.5% with 11 fins to 67.0% with 13 fins and 67.2% with 15 fins, indicating approximately a 1.0% improvement with increasing fin count. In the 0.75 mm spacing model, effectiveness rose from 70.8% (11 fins) to 71.5% (13 fins) and 72.0% (15 fins), showing a total increase of 1.7%. For the model with a 1.0 mm spacing, effectiveness increased from 73.0% (11 fins) to 75.0% (13 fins) and 75.2% (15 fins), resulting in an overall improvement of about 3%. On the other hand, when the spacing was increased from 0.5 mm to 1.0 mm for a fixed fin count of 11, effectiveness rose from 66.5% to 73.0%, corresponding to a 6.5-point increase, or approximately a 9.8% improvement. These findings demonstrate that increasing both the number of fins and the spacing gradually enhances the thermal performance of the rotary heat exchanger.

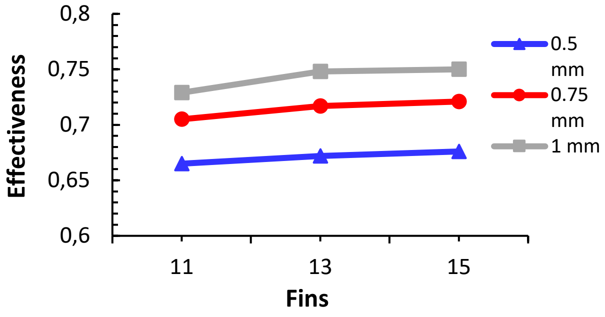
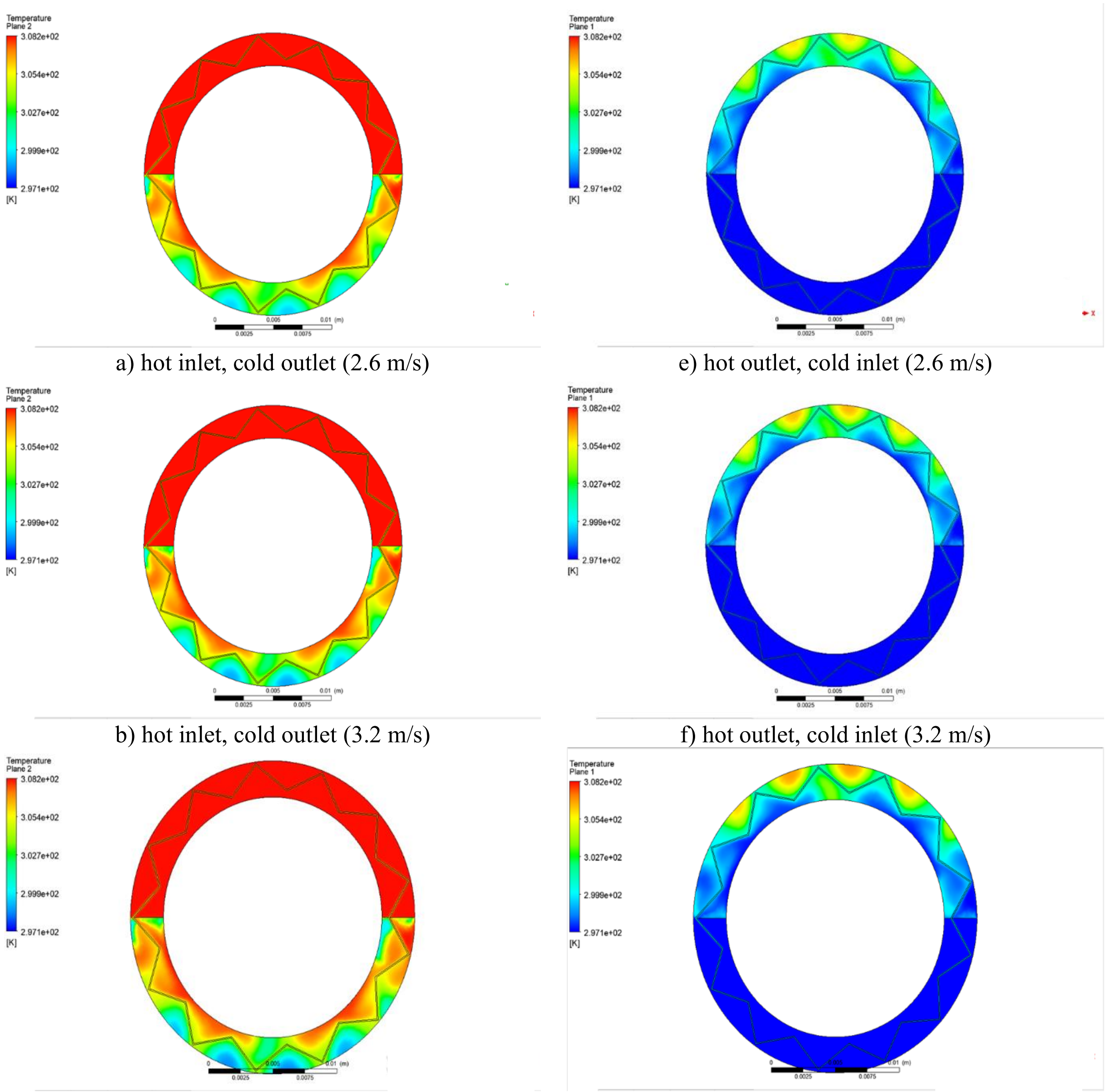


Figure 9. Effectiveness variation for different numbers of fins

Effect of Air Velocity on Performance

Air velocity is a significant factor that influences the boundary layer thickness on finned surfaces and, consequently, the heat transfer coefficient. In this study, the effects of different air velocities on both the temperature distribution and the effectiveness of a rotary heat exchanger were numerically investigated. Additionally, the study considered whether the impact of air velocity varies depending on the number of fins. Figure 10 presents the temperature distributions for the model with 13 fins under different air velocity conditions.



a) hot inlet, cold outlet (2.6 m/s)

e) hot outlet, cold inlet (2.6 m/s)

b) hot inlet, cold outlet (3.2 m/s)

f) hot outlet, cold inlet (3.2 m/s)

c) hot inlet, cold outlet (3.8 m/s)

g) hot outlet, cold inlet (3.8 m/s)

Figure 10. Temperature distributions at the inlet and outlet regions of the fluids at different air velocities

When examining the figure, a common distribution pattern is observed in both the "hot inlet – cold outlet" (a–c) and the "cold inlet – hot outlet" (e–g) contour plots. At lower air velocities, the temperature distribution is relatively more homogeneous, whereas at higher air velocities, more abrupt temperature changes occur. A comparison of Figures 10a, 10b, and 10c shows that with increasing air velocity, although the inner wall exhibits a similar temperature distribution at the cold fluid outlet, more distinct cold zones appear along the outer wall. Similarly, in Figures 10e, 10f, and 10g, as air velocity increases, the inner wall of the hot fluid outlet remains relatively unchanged, while hotter regions develop along the outer wall.

Figure 11 presents a comparative analysis of the effect of air velocity on effectiveness at different airflow speeds and varying numbers of fins. As observed in the figure, increasing the number of fins initially raises the effectiveness; however, with increasing air velocity, effectiveness losses also increase, and the contribution of additional fins diminishes at higher speeds. In parallel with the temperature contours, it is evident that effectiveness decreases as velocity increases. This reduction is approximately 0.9% for 11 and 13 fin, whereas for the 15 fin configuration, it reaches around 1.9%. The present model predicts effectiveness values 5–11% higher than those reported by Çiftçi and Sözen [1] under similar laminar conditions, attributed to finer boundary-layer resolution and segment-level modeling.

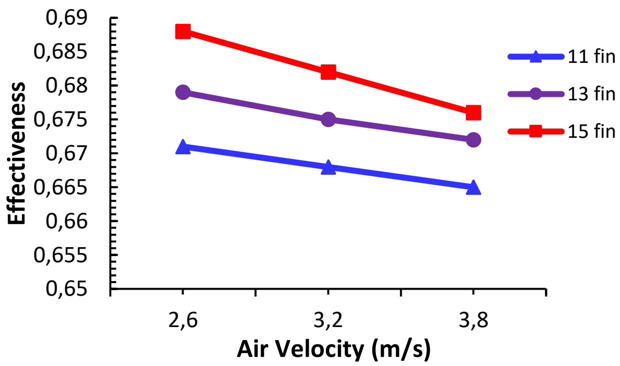


Figure 11. The effect of air velocity on effectiveness for different fin numbers

Conclusion

In this study, the thermal performance of a rotary regenerative heat exchanger was numerically investigated by examining the effects of fin number, fin spacing relative to the inner diameter, and air inlet velocity using a simplified annular segment model. The primary objective was to identify how geometric and operating parameters influence thermal effectiveness under consistent numerical conditions.

The results indicate that increasing the fin number enhances the heat transfer surface area and leads to measurable improvements in thermal effectiveness. Similarly, enlarging the fin spacing from 0.5 mm to 1.0 mm significantly improves thermal performance, with effectiveness increases of up to approximately 9.8% observed across configurations. Among the investigated cases, configurations with 13–15 fins and 1 mm fin spacing exhibited the most favorable thermal behavior, particularly under lower inlet velocity conditions.

Increasing air velocity was found to reduce effectiveness due to decreased contact time and incomplete thermal boundary layer development. Therefore, from a purely thermal perspective, moderate fin numbers combined with larger spacing and lower inlet velocities provide the most advantageous performance trends within the studied parameter range.

Numerical analyses conducted on a small-scale, symmetric cross-section of a rotary regenerative heat exchanger evaluated the effects of key parameters such as fin number, fin placement, and air velocity on thermal performance. Although the studied model represents only a limited section of the entire system, the obtained results demonstrate that design parameters cause measurable changes in effectiveness. In particular, increasing the number of fins and enlarging the fin spacing from the inner diameter expanded the heat transfer surface area, resulting in increased effectiveness. However, the magnitude of these changes remained limited within the geometric scale studied.

The present study focuses exclusively on thermal effectiveness trends using a simplified segment-level model. Pressure drop optimization and full-scale system evaluation are considered beyond the scope of this work and are recommended for future investigations. Overall, the findings provide fundamental insight into the sensitivity of thermal effectiveness to geometric variations and offer preliminary guidance for the geometric design of compact rotary regenerative heat exchangers.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Committee Approval and Conflict of Interest Statement

There is no need to obtain permission from the ethics committee for the article prepared. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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