AMERICAN Journal of Engineering,
Mechanics and Architecture
Volume 3, Issue 5, 2025 ISSN (E): 2993-2637

Mixed Convection Heat Transfer Inside Cavities with a Rotating Inner Cylinder with or without Moving Wall: A Review

Hajer Mohammed, Prof. Dr. Akeel Abdullah Mohammed
Al-Nahrain University, College of Engineering, Mech. Eng. Dept.

Abstract: Mixed convection heat transfer in enclosures with a spinning inner cylinder has attracted considerable research interest due to its relevance in many engineering and technical applications such as electronic cooling, energy systems, and industrial thermal management. This review article presents a comprehensive overview of recent numerical investigations focused on enhancing mixed convection performance via revolving cylinders under numerous boundary and flow conditions. The enhancement techniques are systematically categorised into six main categories: nanofluids and hybrid nanofluids, porous media, ventilated cavities, moving wall enclosures, multi-cylinder configurations, and other enhancement strategies. Each group is analyzed regarding cavity geometry, thermal characteristics, and performance metrics, including Nusselt number behaviour. Summary tables are provided to facilitate comparison across studies. Key trends, limitations, and emerging gaps in the literature are highlighted, offering guidance for future study and optimization of advanced thermal systems involving spinning elements.

Keywords: mixed convection, cavity, rotating cylinder, lid-driven, nanoparticles.

Abbreviations:

Symbol	Meaning
Ri	Richardson number
Re	Reynolds number
Ra	Rayleigh number
Ha	Hartmann number
d	Diameter
r	Radius
Pr	Prandtl number
Gr	Grashof number
Da	Darcy number
MHD	MagnetoHydroDynamics
N	Number of waves
θ	Angle
T	Temperature
ω/Ω	Angular speed
φ	Nanoparticles volume fraction

1. Introduction

Heat transfer by convection is one of the major mechanisms that play a key role in many important engineering and industrial applications. It includes two main types of transfer:

convection, which is the wider range of movement through a fluid, and diffusion, which is the random Brownian movement of individual particles in a fluid [1]. Convection has three main types: forced convection, in which movement is produced by external means; natural convection, in which the movement of a fluid is by buoyancy due to density changes resulting from temperature differences; and finally, mixed convection, which results from the interaction of forced and natural convection together [2].

Cavities are widespread in heat transfer systems, with numerous applications such as heat exchangers, electronic refrigeration units, solar collectors, heating, ventilation, air conditioning (HVAC) systems, and renewable energy. To improve the thermal performance of these systems, numerous studies have been conducted to improve and develop heat transfer techniques within these cavities. One of the most prominent of these techniques is the introduction of a rotating cylinder within a cavity, which has a direct impact on thermal dynamics and flow patterns, particularly when used in conjunction with other enhancement techniques such as magnetic fields, thin media, moving walls, or nanofluids. Therefore, this concept is of great importance in industrial applications that rely on rotating parts, such as rotary motion heat exchangers, turbines, engines, etc. [3-6]. Therefore, understanding the effect of cylinder rotation and other associated factors on the mixed heat load is essential for designing more efficient thermal systems.

Recent years have seen extensive research effort, represented by numerous numerical studies addressing the heat transfer behavior in cavities containing spinning cylinders under various situations. The development approaches employed have varied, including the use of nanofluids, the incorporation of porous media, the introduction of ventilation holes, and the modification of cavity shapes or boundary conditions. Accordingly, this paper intends to provide a thorough, systematic assessment of the most significant numerical research in this field, categorizing it according to the type of optimization technique used. It also seeks to analyze the findings of existing research, identify overarching patterns, in addition to highlighting research gaps and recommending future paths that could contribute to improving the performance of mixed-convection heat transfer systems in cavities equipped with analyze the findings of existing research, identify overarching patterns cylinders.

2. Review Methodology

This study systematically reviewed numerous studies on mixed-convection heat transfer within cavities containing rotating circular cylinders. These studies were selected based on the following criteria:

1. Numerical studies of cavities containing multiple cylinders under different boundary conditions.
2. Studies that employed various heat transfer enhancement methods using diversity techniques, including nanofluids, magnetic fields, porous media, various cavity shapes, etc.
3. Research papers and articles that provide clear data on the governing criteria, published over the past two decades.

To ensure clarity during the formatting and subject uniformity, these selected studies were classified into six main groups:

1. Cavities with multiple rotating cylinders
2. Moving-wall cavities
3. Cavities containing nanofluids and hybrid nanofluids
4. Cavities containing porous media
5. Ventilated cavities
6. Cavities with other optimization mechanisms

Each of these groups was analyzed in terms of governing parameters, geometry, optimization strategies, and key findings or discoveries. Tables were also created to compare the basic data summaries for each category and facilitate cross-analysis between these studies.

3. Enhancement in mixed convection inside Enclosures

3.1 Using multiple rotating cylinders

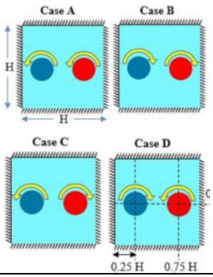
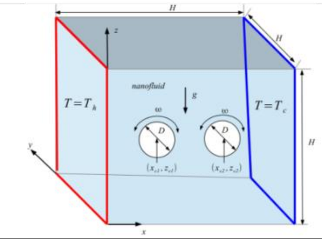
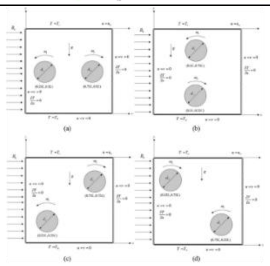
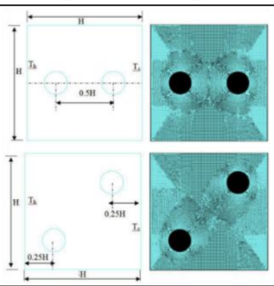
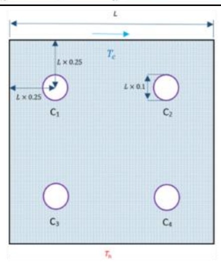
Many researchers investigated numerically how to enhance mixed convection heat transfer in cavities with several revolving inner cylinders under various conditions [7-15]. Further methods to enhance the heat transfer process could include using various cavity configurations, fluids, cylinder harmonic motion, and so on.

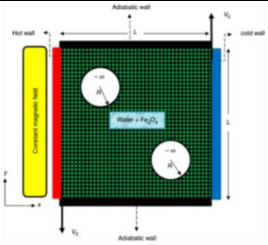
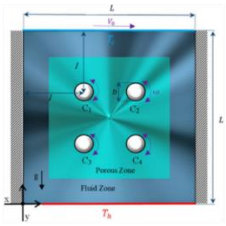
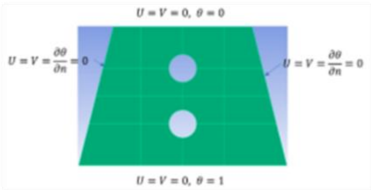
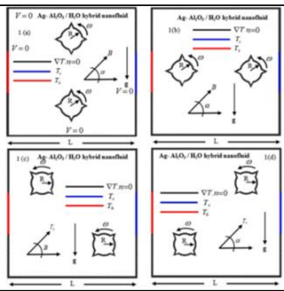
- Mehdi and Majid [7] used a square cavity containing two hot and cool rotating cylinders and a non-Newtonian nanofluid. Four examples of cylinders rotating in various directions were examined. They found that the thickness of shear of the nanofluids or shear behavior could drastically alter forced convection's impact on heat transfer effectiveness, and the effectiveness of heat transfer could be adversely affected by the values of the Rayleigh number, non-Newtonian power law index, and Richardson number.
- In a cavity in three dimensions with two spinning, thermally insulated circular cylinders, Fatih and Hakan [8] conducted nanofluid's mix convection. Which is depending on the rotation's direction, it was shown that the Nusselt number increases when the cylinders are rotated. there is also an increase between the hybrid nanofluid and the average Nusselt number.
- The impact of the two revolving cylinders over the mixed laminar convection of nanofluids inside a lid-driven cavity in the presence or absence of an external magnetic field was investigated by Garmroodi et al. [9]. The influence of the external magnetic field is greater when the two cylinders are oriented vertically.
- In a cavity that was heated differently, Khanafer et al. [10] investigated how the two revolving cylinders impacted mixed convection. The direction of the cylinder rotating speed was found to have a significant impact on the Nusselt mean, and the flow pattern and isotherms are affected by both the magnitude and direction of the cylinder rotational speed.
- Four revolving cylinders with harmonic motion were used by Nima et al. [11] to quantitatively study the impact on the combined convection of the Cu-water nanofluids in a cavity driven by a square shell at various wall temperatures. It was demonstrated that the concentration of nanoparticles, the cylinder's angular velocity, and the kind of rotation all had an impact on heat transfer.
- Pouya et al.'s [12] focused on the effects of porous media, MHD imprints, and spinning cylinders at three distinct temperature settings on a square cavity's mixed convection of a nanofluid. The porous media seemed to have a positive effect on raising the rate of heat transfer, whereas the magnetic field with the porous media combination may enhance or limit heat transfer.
- Nima and Davood [13] studied the effect of four rotating cylinders on the mixed convection of a nanofluid in a two-dimensional square container containing a porous mass at its center, driven by a simple harmonic function. It was shown that the decline in Richardson's and Darcy's numbers leads to the rise in the average Nusselt number, which indicates that variations in porosity don't significantly impact heat transfer.
- Bader [14] studied the impact of rotational speed and direction on mixed convection heat transfer around two revolving cylinders in a trapezoidal chamber filled with a porous substance. It was found that the Richardson number, along with the revolving cylinders' speed, direction, and placement, all have a significant impact on heat transmission.

- ➢ In a partially heated square cavity filled with nanofluids and including two rough spinning cylinders with an external magnetic field, Rowsanara et al. [15] investigated the mixed convective flow. The findings demonstrate that as hybrid nanoparticle size and magnetic field strength increase, mixed convective heat transfer diminishes.

Most studies in this group have indicated that increasing the number of rotating cylinders improves heat transfer efficiency, especially when used with nanofluids or porous media. Harmonic motion and hybrid nanofluids also lead to higher Nusselt numbers. However, some inconsistencies appear in the presence of magnetic fields or when using large nanoparticles, as reported by Rossana et al. [15], where heat transfer decreases. This indicates that despite the improvement in cylinder rotation, its effectiveness is highly dependent on other factors such as fluid properties, fluid arrangement, and external fields.

Table 1 Mixed convection in an enclosure with multiple inner cylinders rotation

Authors	Geometry	Parameters' Range
Mehdi and Majid [7]		Cu-water nanofluid $Ra = 10^5$ $Ri = 1$ $d = 25nm$ $\varphi = 0.04$
Fatih and Hakan [8]		Cu, AlO, Al_2O_3, and TiO nanoparticles $Ra = 10^5$ $\varphi = 0, 0.02, 0.04$ $\Omega = -1000, 0, 1000$ $\Omega = -100, 0, 100$
Garmroodi et al. [9]		Cu-water nanofluids $\varphi = 0,0.1,0.2$ $\Omega = 0,10,25$ $Re = 100$ $d = 0.2\ L$ $Ha = 0$
K. Khanafer et al. [10]		Location of the cylinders (horizontal v/s diagonal) $0.01 < Ri < 10$ $Ra = 10^4, 10^5, 10^6$ $0 < \Omega < 100$ $Pr = 0.7$ $100 < Re < 500$
Nima et al. [11]		Cu–water nanofuid $0 \leq \varphi \leq 0.03$ $0.1 \leq Ri \leq 10$ $d = 0.1\ L$ $\Omega = 5$ $Re = 862.34214$, $Ri=0.1$ $Gr = 74,363.3974$

Pouya et al. [12]		Fe_2O_4–water Ri = 1 to 100 Ha = 0 to 30 Da = 0.001 to 0.1 φ = 0 to 0.03 constant angular velocity (− ω)
Nima and Davood [13]		Cu-water nanofuids $10^{-5} \leq Da \leq 10^{-2}$ $0.1 \leq Ri \leq 10$ $0 \leq \varphi \leq 0.03$ $\Omega = 5$
Bader [14]		CW-CW and CCW-CW casing Pr=0.7 Ri=0.01, 1, 5,10 ω =0.5, 10
Rowsanara et al. [15]		H_2O - Ag and Al_2O_3 $0 \leq \omega \leq 50$ $0 \leq Ha \leq 50$ $0\% \leq \varphi \leq 5\%$ magnetic inclination angle = 0^o to 135^o

3.2 Using a moving wall, and single or multiple inner cylinder rotation

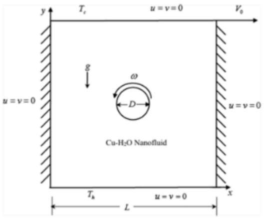
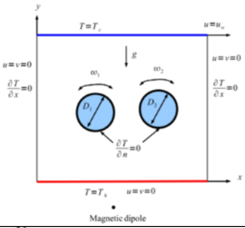
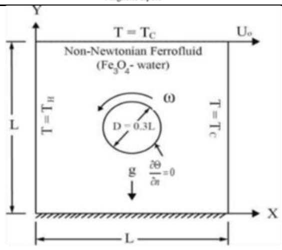
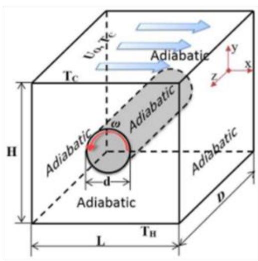
These studies [16-23] are focused on how the process of heat transfer can be improved by using different parameters around the cylinder inside an enclosure that has a lid-driven. The researches listed in Table 2 shows a summary of these studies. It might entail adding additional boosting methods like ferrofluids, nanofluids, and one or more cylinders.

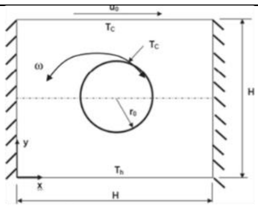
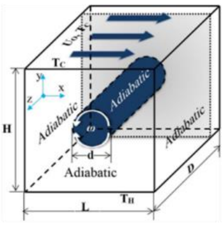
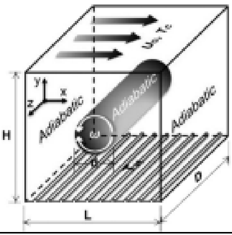
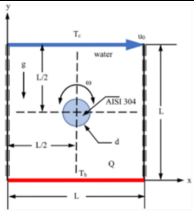
- In a study by Dipankar et al. [16], it was concluded that the concentration of Cu nanoparticles and the cylinder's rotation speed significantly impact the square enclosure's heat transfer with a movable lid, which was heated differently.
- Fatih and Hakan [17] looked into how two revolving cylinders affected a moving cavity with a magnetic fluid-filled cover and mixed convection. Clockwise cylinder rotation led to moderate gains in heat transfer.
- In a square container driven by a lid, Khan et al. [18] investigated the impact of a revolving drum on mixed convection using a non-Newtonian magnetic fluid. Improved heat transfer was discovered to be a result of raising the rotation speed, power law index, and Richardson number.
- Using a revolving cylinder that was thermally insulated, Ali and Shian [19] investigated the heat transfer mechanisms (forced and free convection) in the three-dimensional cavity that was differentially heated. It was shown that the cylinder's rotational speed and Reynolds number have a major impact on the flow patterns and the thermal fields.
- A rotating cylinder inside a cavity driven having moving wall was studied by Khanafer and Aitha [20]. A rotating cylinder inside a cavity can achieve maximum heat transfer levels compared to a non-rotating cylinder.

- Ali and Shian [21] studied a combination of SiO2-H2O and pure water H2O nanofluids in a three-dimensional cubic container that was differentially heated and had a moving wall. The insulated cylinder in the center of the container rotated at varied speeds. There were nonlinear increases in the Nusselt number when the nanofluids were utilized in place of water.
- Ali and Shian [22] used a rough bottom wall heated with two types of artificial ribs (R-s) and (R-c) to transfer heat by unsteady mixed convection inside a moving top wall cavity which is a three-dimensional with a revolving cylinder in the center of it, the use of artificial ribs considerably boosted the rate of heat transfer.
- Md. Jisan et al. [23] examined the effect of a solid cylinder with a thermally conductive surface on a movable wall-driven square enclosure internal heat generation and mixed convection. The solid cylinder's rotational direction and speed have less of an impact on the system's thermal performance, but as Reynolds and Grashof numbers rise, so does the heat transfer process.

Research results involving moving-shell cavities and rotating cylinders have shown consistent improvements in heat transfer efficiency due to improved flow interaction. However, the improvement varies depending on the cylinder rotation direction and fluid properties. For example, Ali and Shiyan [21] reported nonlinear enhancements using nanofluids. Jis et al. [23] found only a minor effect of cylinder rotation, highlighting that fixed cylinders limit the rotational effect. Therefore, the motion between the moving walls and the cylinder motion must be controlled to achieve maximum improvement.

Table 2 Mixed convection in an enclosure with a moving wall, and single or multiple inner cylinder rotation

Authors	Geometry	Parameters' Range
Dipankar et al. [16]		$Cu\text{-}H_2O$ nanofluid $1 \leq Ri \leq 10$ $0 \leq \Omega \leq 5$ $0 \leq \varphi \leq 0.20$ $Gr = 10^4$
Fatih and Hakan [17]		$0.25 \leq \Omega_i / \Omega_j \leq 4$ $0.5 \leq D_i/D_j \leq 2$ $100 \leq Re \leq 1000$ $-400 \leq \Omega \leq 400$
Khan et al. [18]		Fe_3O_4 -water Ri = 0.1 – 10 n = 0.5 - 1.5 Ω = 0 – 15 φ = 0 - 0.05
Ali and Shian [19]		Re = 5000, 10000, 15000, and 30000 $0 \leq \Omega \leq 10$

Khanafer and Aitha [20]		Pr = 0.7 Re = 100 Ri = 1 ϖ = 0.5 r_o/H = 0.2
Ali and Shian [21]		water H_2O and SiO_2-H_2O nanofluids Re = 5000 and 10,000 $-5 \leq \Omega \leq 5$ Ri = 1, 5, 10
Ali and Shian [22]		artificial rib types (R-s and R-c) Re = 5000 and 10,000 $-5 \leq \Omega \leq 5$ Ri = 1, 5, 10
Md. Jisan et al. [23]		Re = 100 Pr = 5.85 $0.1 \leq Ri \leq 10$ $10^3 \leq Gr \leq 10^5$ $-2 \leq Re_c \leq 2$

3.3 Enhancement Using Nanofluids and Hybrid Nanofluids

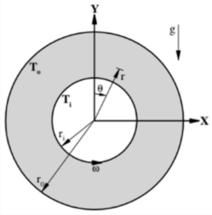
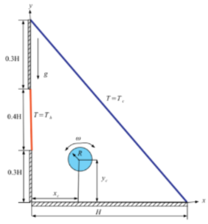
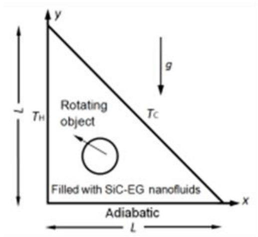
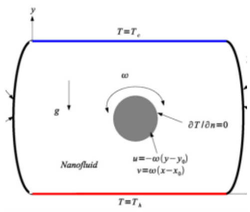
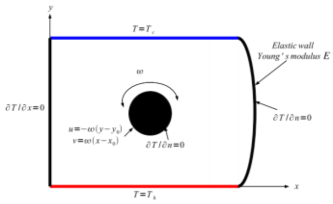
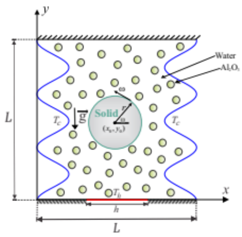
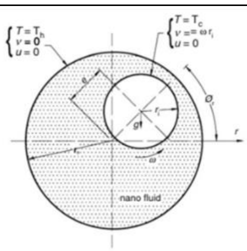
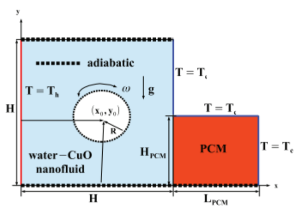
The addition of nanoparticles or hybrid nanoparticles to the base fluid, which raises its thermal conductivity, is a useful technique for improving heat transmission. Nanofluids, or hybrid nanofluids, have been used in the research of numerous researchers [24-38] as shown in Table 3.

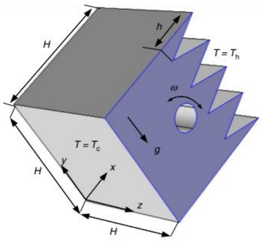
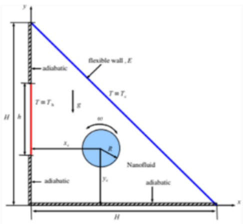
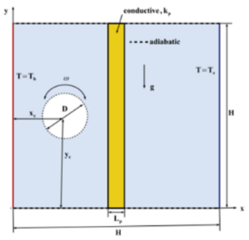
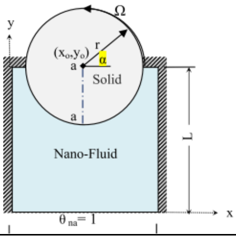
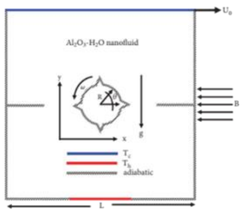
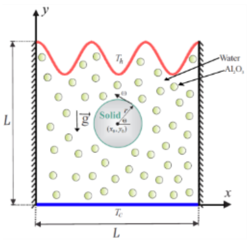
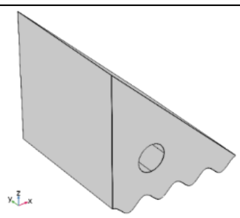
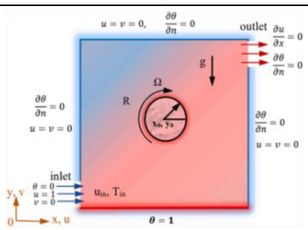
- A concentric annulus with an inner rotating cylinder was used as a case study by G. A. Sheikhzadeh et al. [24] to determine how nanofluids affected mixed laminar mixed convection. The results show that the average Nusselt number decreases as the Reynolds number increases.
- Fatih and Hakan [25] found in a triangular enclosure containing Cu–water nanofluid that as the Grashof number increases, the rise in both the overall entropy generation and the average Nusselt number occurs when the cylinder rotates at a higher angular velocity.
- In a triangular cavity containing silicon carbide (SiC-EG) and ethylene glycol, Yu-fei WANG et al. [26] indicated that the average Nusselt number increases with the addition of nanoparticles to the fluid and that the direction of rotation influences the thermal performance.
- In a volumetric heat-generating cavity containing a nanofluid with adiabatically elastic side walls, Fatih and Hakan [27] found that while the inner Rayleigh number decreased, heat transfer both locally and on average rose. The greatest outcomes in terms of enhancing and raising heat transfer were obtained by employing cylindrical nanoparticles.
- Fatih et al. [28] discovered that the cylinder's rotation in both directions increases the average heat transfer, and also that the cylindrical shapes perform best in this regard, while spherical shapes perform the worst in a square cavity with a spinning cylinder and a flexible side wall.

- In an enclosure filled with a nanofluid that had wavy side walls and a spinning cylinder in the center, Ammar et al. [29] noted that the heat exchange rate increases as the heater's length component and the size of the nanoparticles grow.
- In a cylindrical chamber with an internally rotating central cylinder, Milad et al. [6] demonstrated that the average Nusselt number on the inner cylinder wall rises as the volume fraction of the nanofluid does.
- The mixed convection MHD of aqueous nanofluid inside a 3D cubic cavity with a vertical surface attached to a phase change material (PCM) and a spinning hot circular cylinder in the middle was studied by Ali and Fatih [30]. The heat transfer improvement increased as the original fluid's thermal conductivity ratio (PCM) increased.
- In the three-dimensional corrugated enclosure using a revolving adiabatic cylinder and containing a nanofluid of carbon nanotubes, Fatih et al. [31] found that the cylinder angular rotation speed and solid particle volume fraction are significantly more effective in enhancing heat transfer than surface corrugation parameters.
- Fatih et al. [32] noticed that heat transfer was particularly improved for the bottom part of the triangular cavity containing nanofluids because of the addition of nanoparticles in comparison to the base fluid.
- In a three-dimensional cubic container divided by a conductive partition, Fatih and Hakan [33] investigated the adiabatic inner circular cylinder's influence on heat transfer by convective features of a CNT aqueous nanofluid. The results showed that when CNT nanoparticles are embedded, the average heat transfer increases.
- In a study by Saba et al. [34], the influence of a rotating, semi-submerged conductive cylinder with its top wall on mixed convection within an enclosure with a lower wall that is heated and contains a Cu-water nanofluid was examined. The effect of convection is greater with increasing angular velocity of the rotating cylinder, and as the geometric aspect ratio increases, the opposite performance is observed was noted.
- Mohammad et al. [35] proved that raising the rough drum's rotation speed in a square hollow with triangle components, horizontal bases, and an external magnetic field significantly affects the temperature distribution and rotation of the revolving drum.
- In a three-dimensional wavy tank with a central revolving cylinder filled with an aqueous Al_2O_3 nanofluid, Ammar et al. [36] demonstrated that since the oscillation and the Richardson number fall, the higher nanoparticle volume percentage might result in improved heat transmission.
- Bellakhdar et al.'s study [37] showed that higher Darcy and Hartmann numbers produce greater rates of heat transfer in a hybrid nanofluid inside a three-dimensional porous cavity with a revolving cylinder.
- Falah et al.'s study [38] investigated mixed convection across a hybrid nanofluid by using a square cavity with a revolving cylinder in the center of the fluid. The findings demonstrate that a rise in the Reynolds, Richardson, and angular rotation speed is correlated with a rise in the average Nusselt number.

Most studies have shown that adding nanoparticles to the base fluid significantly increases heat transfer by improving thermal conductivity and Brownian motion. However, some conflicting results have emerged when studying the role of the Reynolds number. While most studies have reported positive results, Sheikhzadeh et al. [24] observed that the Nusselt number decreases with increasing Reynolds number. This suggests that high flow velocity may reduce the thermal contact time, potentially diminishing the advantages of nanofluids. In addition, particle shape and composition may affect the results, with cylindrical particle shapes often outperforming spherical shapes.

Table 3 Heat Transfer Enhancement Using Nanofluids.

Authors	Geometry	Parameters' Range
G. A. Sheikhzadeh et al. [24]		Al_2O_3-water Ra $=10_2$ to 10_5 Re =1 to 300 $\varphi = 0.01$ to 0.06 $-180 \leq \theta \leq 180$
Fatih and Hakan [25]		Cu–water nanofluid $10^4 \leq Ra \leq 10^6$ $0 \leq Ha \leq 50$ $-20 \leq \omega \leq 20$ $0 \leq \varphi \leq 5\%$
Yu-fei WANG et al. [26]		SiC-EG nanofluids Pr = 7.0 $-5\times10^3 \leq \Omega \leq 5\times10^3$ R=0.05, 0.1, 0.15, 0.2 φ=0, 0.01, 0.02, 0.03, 0.04 Ra=10^4 , 10^5, 10^6 , 10^7
Fatih and Hakan [27]		SiO_2 –water nanofluid $10^3 \leq Ra_E \leq 5\times10^5$ $-2000 \leq \Omega \leq 2000$ $10^4 \leq Ra_I \leq 10^6$ φ = 0, 0.01, 0.02, 0.03
Fatih et al. [28]		SiO_2 –water nanofluid $10^3 \leq Ra_E \leq 5\times10^5$ $10^4 \leq Ra_I \leq 10^6$ $-2000 \leq \Omega \leq 2000$ φ = 0, 0.01, 0.02, 0.03
Ammar et al. [29]		Al_2O_3–water nanofluid $10^3 \leq Ra \leq 10^6$ $0 \leq \Omega \leq 750$ $0 \leq \varphi \leq 0.04$ $0 \leq N \leq 4$
Milad et al. (2018), [6]		water–Al_2O_3 $10^3 \leq Ra \leq 10^5$ $0.1 \leq Ri \leq 100$ $0.0 \leq \varphi \leq 0.03$ $0^o \leq \theta \leq 360^o$
Ali and Fatih [30]		CuO-water nanofluid Ha = 0 to 100 Ra = 10^5 to 10^6 Ω = -100 to 100 φ = 0 to 0.04 Height = 0.2H to 0.8H

Fatih et al. [31]		carbon nanotube-water Ra = 10^4 to 10^6 Ω = -50 to 50 Height = H / 10 to H / 3 triangular waves = 1 to 16 φ = 0 to 0.04
Fatih et al. [32]		CuO-water nanofluid $1 \leq Ri \leq 100$ Ω = -3000 to 3000 φ = 0 to 0.05 Ra = 10^4 to 10^6
Fatih and Hakan [33]		CNT water nanofluid $1 \leq Ri \leq 100$ Ω = - 34724 to 34724 thermal conductivity ratio = 0.1 to 100 φ = 0 to 0.03
Saba et al. [34]		Cu-water nanofluid $0 \leq \Omega \leq 1000$ $5 \leq h \leq 20$
Mohammad et al. [35]		Al_2O_3-water nanofuid $0 \leq Ha \leq 50$ $0 \leq \varphi \leq 0.05$ $10 \leq Re \leq 200$
Ammar et al. [36]		Al_2O_3 –water nanofluid $0.01 \leq Ri \leq 100$ $0 \leq \varphi \leq 0.04$ Ω = 15 $0 \leq N \leq 4$
Bellakhdar et al. [37]		Fe_3O_4/MWCNT-water $-500 < \Omega < 1000$ $0 < Ha < 100$ N = 1, 2, 3, 4
Falah et al. [38]		Ag-MgO nanoparticles $-25 < \Omega < 25$ $10 \leq Re \leq 100$ $0 \leq Ri \leq 35$ Pr = 6.2

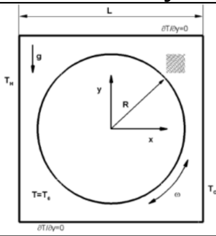
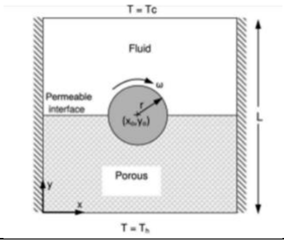
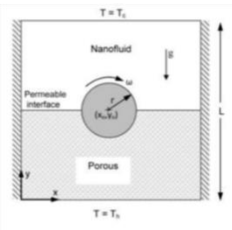
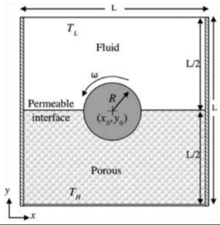
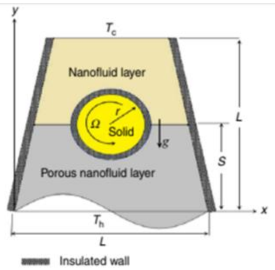
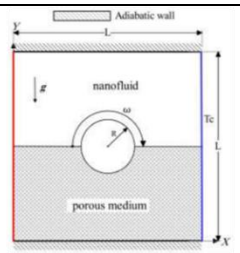
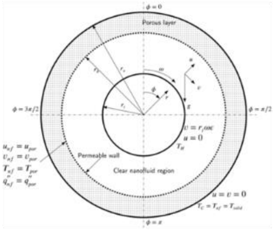
3.4 Enhancement Using Porous Media

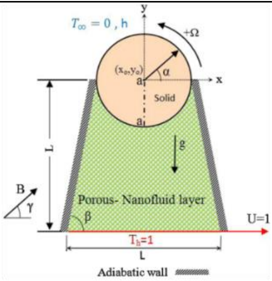
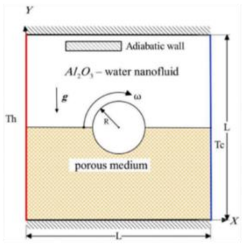
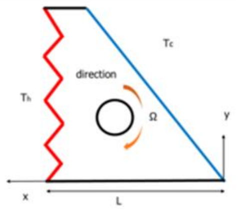
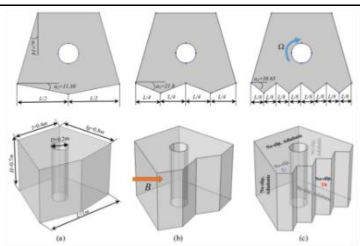
A comprehensive overview of the controlling parameters, ranges, and geometries is provided by these research [39-48] addressing the improvement of heat transmission in cavities through the use of porous media. This information is summarized in Table 4.

- Aydin [39] found that the forced convection system benefited more from rotation compared to natural convection in a square enclosure that is filled with porous material or a transparent liquid with a rotating inner.
- In a cavity with a rotating thermal cylinder and a superposed fluid and porous media, Ali et al. [40] concluded that the cylinder size has an impact on both average and local heat transfer.
- Fatih et al. [3] studied the mixed convection of a square cavity divided into two compartments. One compartment held a CuO nanofluid, while the other was a porous medium with a rotating, temperature-controlled cylinder. When compared to a fixed cylinder, the larger volume cylinder showed a more noticeable angular rotation speed impact on improving heat transfer.
- Laxman and colleagues [41] discovered that heat transport in a square enclosure having a centrally rotating cylinder and containing a porous fluid compound is at its lowest and the system is more stable at lower Darcy numbers.
- Ahmed et al. [42] used a trapezoidal container with a sinusoidal bottom wall and a revolving inner cylinder. It was observed that the Nusselt number rises with the increase in the cylinder's radius, angular rotational velocity, solid volume, Rayleigh number, and Darcy number.
- A square two-layer cavity having isothermal rotating cylinder and containing Al_2O_3-water nanoparticles and nanoporous medium was used in a numerical investigation of mixed convection by Ahmed and Khaled [43]. A steep temperature gradient and a discernible increase in flow intensity are apparent as the Rayleigh numbers rise, and the values rise as the cylinder rotates.
- The decrease in the entropy generation and the mixed convection in a ring with a heated, rotating center cylinder of a liquid flow containing single-walled carbon nanotubes (SWCNTs) as the Reynolds number decreases was noted by Oktay et al. [44].
- Farooq et al. [45] concluded that the inclination angle of the magnetic field has a major impact on the thermal performance inside a trapezoidal cylindrical container containing a nanofluid of copper and water saturated with a porous media.
- Khaled and Ahmed [46] used a square container with two layers and a spinning circular cylinder in the center to transfer heat by mixed convection of a nanofluid. The findings indicate that the average Nusselt number rises with increasing values of the solid volume fractions, Rayleigh number, and Darcy number at any cylinder radius.
- Aissa et al. [47] investigated the aqueous nanofluid's mixed convective heat transfer in a three-dimensional cavity with a central rotating cylinder. The findings indicated that for optimal heat transfer, the hot zigzag should be single, the Hartmann number should be less than zero, and the Darcy number should be greater than 10^{-3}.
- Using a rotating tube and a porous trapezoidal container, a hybrid nanofluid, Apichit et al. [48] found that as the nanoparticle size ratio, Darcy number, and inner tube velocity increase, heat transmission intensifies.

In general, porous media stabilize flow patterns and improve heat transfer by increasing thermal contact. However, the effect of the Darcy number is not always constant in all cases. Some studies, such as Ahmed et al. [42], have indicated that increasing the Darcy number improves thermal performance, while Laxman et al. [41] observed that under similar conditions, efficiency decreases. This discrepancy may arise from fluid viscosity, porosity, or thermal conductivity differences.

Table 4 Heat transfer enhancement using porous media

Authors	Geometry	Parameters
Aydin [39]		$Gr = 10^6$ $Gr/Re^2 = 0.0625$ to 10^2 $Da = 10^{-2}, 10^{-3}, 10^{-4}$ $A = 0.8$
Ali et al. [40]		$Da = 10^{-5}$ to 10^{-2} $Ra = 10^3$ to 10^6 $\Omega = 0$ to 6000 $R = 0.1$ to 0.3
Fatih et al. [3]		CuO-Water nanofluid $\varphi = 0$ to 0.05 $Da = 10^{-5}$ to 10^{-2} $Ra = 10^3$ to 10^6 $\Omega = 0$ to 6000
Laxman et al. [41]		$Da = 10^{-2}$ to 10^{-6} $0.1 \leq Ri \leq \infty$ $10^3 \leq Ra \leq 10^6$
Ahmed et al. [42]		CuO–water nanofuid $10^3 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.06$ $10^{-5} \leq Da \leq 10^{-2}$ $0 \leq \Omega \leq 6000$ $1 \leq N \leq 3$
Ahmed and Khaled [43]		Al_2O_3-water $Da = 10^{-3}$ $10^3 \leq Ra \leq 10^6$ $\Omega = 0$ to 6000 $\varphi = 0.06$
Oktay et al. [44]		(SWCNT)–water $10^4 \leq Ra_E \leq 10^6$ $10^{-4} \leq Da \leq 10^{-6}$ $50 \leq Re \leq 10^3$

Farooq et al. [45]		Cu-water nanofluid Ha = 0 to 100 Ri = 0.01 to 100 R = 0.2 to 0.4 Da = 10^{-5} to 10^{-1} φ = 0 to 0.1
Khaled and Ahmed [46]		Al_2O_3–water $10^{-2} \le Da \le 10^{-5}$ $10^{3} \le Ra \le 10^{6}$ $0 \le \varphi \le 0.06$
Aissa et al. [47]		Fe_3O_4/MWCNT Da = 10^{-5} to 10^{-2} Ha = 0 to 100 $\Omega = -500$ to 1000 N = 1, 2, 4
Apichit et al. [48]		MoS_2 and G.O. nanoparticles Ω = 100, 250, 500 $0 \le \varphi \le 0.06$ N = 1, 2, 4 Ha = 0 to 100 $10^{-2} \le Da \le 10^{-5}$

3.5 Enhancement Using Vented Cavity

How various parameters might be utilized to enhance the process of heat transfer within a spinning inner cylinder in a vented cavity is the main topic of this section's review of research [49-53], see Table 5. Additional techniques for improvement, such as magnetic fields, nanofluids, and generalized neural networks, may be employed.

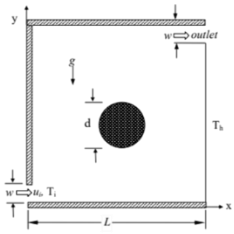
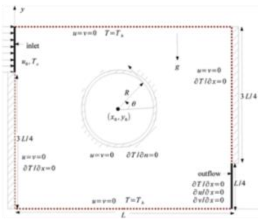
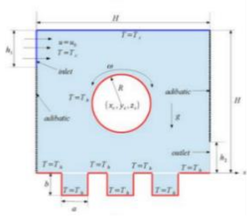
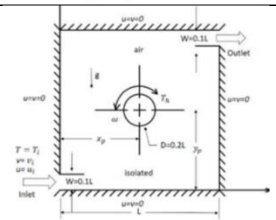
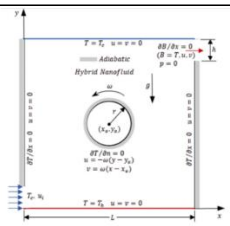
- The influence of a horizontal solid circular cylinder on the steady laminar mixed convection flow within a square enclosure with vents was examined by Md. Mustafizur et al. [49]. The average heat transfer process in the cavity has been found to be considerably influenced by the Richardson number and cylinder diameter, respectively.
- Fatih and Hakan [50] found that the performance of mixed convection in a square cavity with a thermally insulated rotating cylinder and air holes filled with nanofluids is increased with an increase in the nanoparticle size ratio.
- In a three-dimensional vent enclosure with inlet and exit ports, Fatih and Ali [51] showed that quick counterclockwise rotation produces a higher heat transfer rate in a cavity with the effects of surface undulation, a homogenous magnetic field, and a rotating inner circular cylinder.
- Shadman et al. [52] investigated the effect of direction on a rotating cylinder heated isothermally in a square cavity with sufficient ventilation. They showed that the average Nusselt number at the cylinder wall improves.
- Laith et al. [5] looked at the impact of a spinning adiabatic cylinder on hybrid nanofluid convection within a vented cavity. It was discovered that while the cylinder's

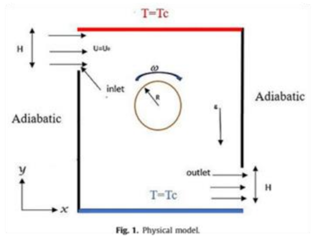
counterclockwise rotation boosts convective heat transfer, increasing the quantity of solid particles improves energy transmission in the nanofluids.

- In a vented chamber with an interior rotating cylinder maintained at a constant temperature, Aissa et al. [53] studied the mixed convection of a non-Newtonian, incompressible, force-law hybrid nanofluid. A counterclockwise rotation of the stationary cylinder was found to improve convectional heat transmission, particularly when the cylinder gets close to the hot wall.

Most studies on ventilation cavities have agreed that heat transfer is improved due to secondary flows and enhanced fluid circulation. Increasing nanoparticle concentration and rotation speed also positively impact heat transfer. Furthermore, there is a lack of research on the precise location of the cylinder relative to the ventilation cavities, which may play a significant role in improving convection.

Table 5. Heat Transfer Enhancement Using a vented cavity with a rotating inner cylinder

Authors	Geometry	Parameters
Md. Mustafizur et al. [45]		Pr = 0.71 $0.2 \leq D \leq 0.6$ $0 \leq Ri \leq 5$ Ra = 0.0, 10^5
Fatih and Hakan [50]		Al_2O_3 - water Re = 50 to 300 Gr = 10^3 to 10^5 φ =0 to 0.05 Ω = - 5 to 5
Fatih and Ali [51]		CuO-water Ha = 0 to 1000 Ri = 0.01 to 100 Ω = -30 to 30 φ = 0 to 0.04 N = 1 to 20
Shadman et al. [52]		$1 \leq Re \leq 500$ Ri=1 X_p = 0.25, 0.5, 0.75 Y_p= 0.25, 0.5, 0.75
Laith et al. [5]		Al_2O_3 - Cu/ water $0 \leq \varphi \leq 0.02$ $50 \leq Re \leq 500$ $10^3 \leq Gr \leq 10^5$

Aissa et al. [53]		Al_2O_3–Cu/CMC $0 < Ha < 100$ $-10 \leq \Omega \leq 10$ $50 \leq Re \leq 500$ $10^3 \leq Gr \leq 10^5$

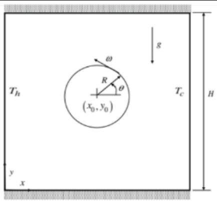
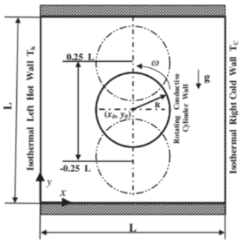
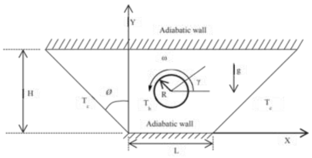
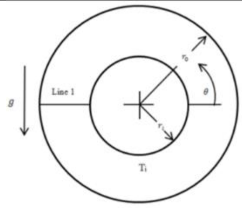
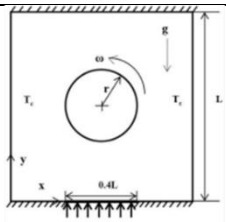
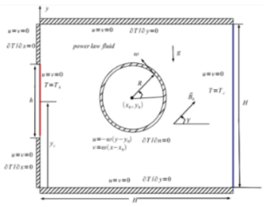
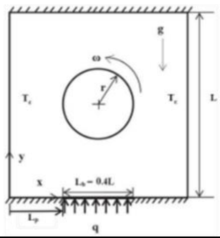
3.6 Enhancement Using Other Enhancement Parameters

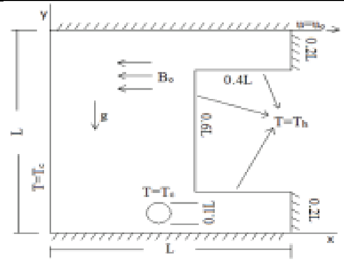
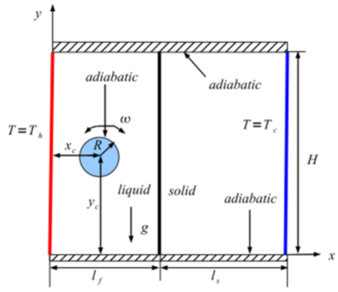
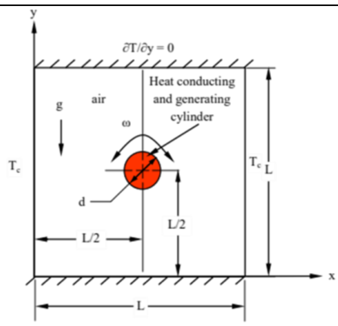
Some authors have conducted studies on enhancing heat transmission utilizing other various factors inside a spinning inner cylinder cavity. A sampling of these works of literature [54-65], together with the many study borders and geometries that may be found in them, are shown and arranged in Table 6.

- Costa and Raimundo [54] from a numerical study in a square container of the effect of a central rotating cylinder on thermal convection concluded that there is a clear relationship between the rotation cylinder and the square cavity's thermal performance.
- Salam and Ahmed [4] found that varying the rotating cylinder locations contributes to improving convective heat transfer inside a square cavity with a closed rotating cylinder in the centre, as does raising the Reynolds and Richardson numbers.
- Mohammed et al. [55] showed that the sidewall inclination angle and the rotating cylinder's inertia effect have the most significant impact on heat transfer characteristics surrounding the active rotating cylinder within a trapezoidal enclosure.
- The influence of a stationary or moving cylinder centered inside a cylindrical hollow on heat transfer via natural and mixed two-dimensional convection was examined by Yadukrishnan et al. [56]. Higher Rayleigh numbers have been shown to result in increased power consumption and better heat transfer.
- Muntasir et al. [57] demonstrated how the rotation speeds and cylinder size impact a square cavity's heat transfer rate inside it is a rotating cylinder that conducts heat.
- Fatih and Hakan [58] looked at the local heat transfer diminishes at the bottom of the heater and improves towards the top of the cavity for a Newtonian fluid and the magnetic field's shear thickness inside a partially heated cavity, containing a constant-temperature central rotating cylinder.
- In a square cavity including a revolving heat-conducting cylinder in the centre, Muntasir et al. [59] investigated the phenomena of mixed convection heat transfer. The flow pattern, temperature field, the position of the heat source, and the cylinder had a major influence on the rate of heat transmission, according to the results.
- Shahriar and Mamun [60] used nanofluids in a C-shaped enclosure to study the impact of a moving cylinder on mixed convection. It was shown that the best heat transfer performance is achieved at a cylinder geometry of (0.85, 0.1).
- A square cavity filled with phase change materials was used by Fatih and Hakan [61] to illustrate the impact of a spinning cylinder on mixed convection. The average Nusselt number rises by 10 to form a stationary cylinder when a larger cylinder is employed in comparison to a smaller cylinder for clockwise cylinder rotation.
- Ehsanul et al. [62] discovered that heat transfer properties are mostly unaffected by the direction of cylinder rotation in a cavity, but thermal performance is significantly impacted by differences in the governing factors and cylinder size.

This group included various techniques such as the use of phase change materials, surface roughness, or altering the cylinder geometry. Enlarging the radius or modifying the cylinder wall shapes often improved the thermal performance, but the rotation direction was slightly different. While some studies and research confirmed its significant effect, Ehsanul et al. [62] reported a small effect, perhaps due to certain boundary conditions or fluid properties. These contradictory results highlight the need for further, more precise studies to isolate the role of each mechanism and quantify its improvement.

Table 6. Heat Transfer Enhancement inside a cavity with a rotating inner cylinder using other parameters

Authors	Geometry	Parameters
Costa and Raimundo [54]		$-1000 \leq \omega^* \leq 1000$ $0^o \leq \theta \leq 360^o$
Salam and Ahmed [4]		Pr = 0.71 Ri = 0, 1, 5, 10 Re =50, 100, 200, 300 thermal conductivity ratios = 0.2, 1, 5, 10
Mohammed et al. [55]		$Gr = 10^3$ to 10^5 $\theta = -15^o, 15^o, 45^o$ $31.62 \leq Re \leq 316.23$ Pr = 0.71 Ri = 1
Yadukrishnan et al. [56]		T = 5K, 50K, 90K $Ri = 10^{-3}$ to 10^3 $0 \leq \theta \leq 400$ Pr=0.7 Aspect ratio =2.5
Muntasir et al. [57]		$Ra = 5x10^4$ Pr=0.7 $0.1 \leq Ri \leq 100$
Fatih and Hakan [58]		$0.01 \leq Ri \leq 100$ $0 \leq Ha \leq 50$ $-50 \leq \Omega \leq 50$ $0^o \leq \theta \leq 90^o$ $0.6 \leq n \leq 1.4$
Muntasir et al. [59]		$0 \leq \Omega \leq 500$ Pr = 0.7 $Ra = 5x10^4$

Shahriar and Mamun [60]		Fe_3O_4 – water Ha = 0 to 40 φ = 0 to 0.20 positions at (0.2, 0.1); (0.45, 0.1); and (0.85, 0.1) $0 \leq \Omega \leq 50$
Fatih and Hakan [61]		$-7.5 \leq \Omega \leq 7.5$ $0 \leq \omega \leq 7.5$ R = 0.05 to 0.1
Ehsanul et al. [62]		CW or CCW direction $1 \leq Ri \leq 2000$ Gr = 1 to $4x10^6$ Ri = 1 d/L = 0.1, 0.2, 0.4

4. Conclusion

Based on the findings of the reviewed studies, several significant trends and opportunities to increase the efficiency of heat transfer in such systems were identified. The current paper reviews the research on heat transfer by mixed convection for some scenarios with varying parameters. The following are, generally speaking, the most significant findings from the papers as mentioned above:

- Increased cylinder rotation speed has been shown to increase fluid flow and heat transmission, which lowers temperature differentials inside the cavity and produces a more uniform heat distribution, boosting heat transfer efficiency.
- When nanofluids are used in cavities, their thermal conductivity is greatly increased, improving the fluid's capacity to transport heat.
- Magnetic fields have been demonstrated to enhance fluid flow in the cavity, lowering temperature differentials across cavity regions and facilitating more uniform heat transfer.
- When compared to single cylinders, research has demonstrated that the use of numerous or variable-dimensional cylinders improves the fluid-cylinder surface contact, increasing the heat exchange area and yielding notable results.
- Corrugated cylinder surfaces and catalytic surfaces (such as porous) have been demonstrated to improve fluid-surface interaction and, hence, boost heat transfer efficiency.

Despite the promising results of this research, there are some limitations that should be considered. Without conducting field trials, many researches are restricted to modeling and simulation, which compromises the precision of their commercial applicability. Also, experiments and simulations are usually conducted on simple and less complex forms than reality, which may limit the accuracy of the results. Furthermore, the efficiency of heat transmission is impacted by the distribution of nanoparticles in fluids, and it is yet unclear how exactly magnetic fields affect these fluids, particularly in systems with spinning surfaces. As a result, it is advised to carry out more field tests, improve the particle distribution, investigate the financial and environmental effects of these technologies, and expand the study of catalytic surface efficiency in heat exchange.

As a result, more theoretical investigations and tests ought to be conducted in the future. The goal is to create theoretical and predictive models that may be used in any cavity.

References

1. Basak, T., Das, D., & Biswal, P. (2018). Heatlines: Modeling, visualization, mixing and thermal management. *Progress in Energy and Combustion Science*, *64*, 157-218. https://doi.org/10.1016/j.pecs.2017.08.003.
2. Rahman, M. M., Billah, M. M., Rahman, A. T. M. M., Kalam, M. A., & Ahsan, A. (2011). Numerical investigation of heat transfer enhancement of nanofluids in an inclined lid-driven triangular enclosure. *International communications in heat and mass transfer*, *38*(10), 1360-1367. https://doi.org/10.1016/j.icheatmasstransfer.2011.08.011.
3. Selimefendigil, F., Ismael, M. A., & Chamkha, A. J. (2017). Mixed convection in superposed nanofluid and porous layers in square enclosure with inner rotating cylinder. *International Journal of Mechanical Sciences*, *124*, 95-108. https://doi.org/10.1016/j.ijmecsci.2017.03.007.
4. Hussain, S. H., & Hussein, A. K. (2011). Mixed convection heat transfer in a differentially heated square enclosure with a conductive rotating circular cylinder at different vertical locations. *International Communications in Heat and Mass Transfer*, *38*(2), 263-274. https://doi.org/10.1016/j.icheatmasstransfer.2010.12.006.
5. Jasim, L. M., Hamzah, H., Canpolat, C., & Sahin, B. (2021). Mixed convection flow of hybrid nanofluid through a vented enclosure with an inner rotating cylinder. International Communications in Heat and Mass Transfer, 121, 105086. https://doi.org/10.1016/j.icheatmasstransfer.2020.105086.
6. Shirazi, M., Shateri, A., & Bayareh, M. (2018). Numerical investigation of mixed convection heat transfer of a nanofluid in a circular enclosure with a rotating inner cylinder. *Journal of Thermal Analysis and Calorimetry*, *133*, 1061-1073. https://doi.org/10.1007/s10973-018-7186-y.
7. Bozorg, M. V., & Siavashi, M. (2019). Two-phase mixed convection heat transfer and entropy generation analysis of a non-Newtonian nanofluid inside a cavity with an internal rotating heater and cooler. *International Journal of Mechanical Sciences*, *151*, 842-857. https://doi.org/10.1016/j.ijmecsci.2018.12.036.
8. Selimefendigil, F., & Öztop, H. F. (2018). Mixed convection of nanofluids in a three-dimensional cavity with two adiabatic inner rotating cylinders. *International Journal of Heat and Mass Transfer*, *117*, 331-343. https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.116.
9. Garmroodi, M. D., Ahmadpour, A., & Talati, F. (2019). MHD mixed convection of nanofluids in the presence of multiple rotating cylinders in different configurations: A two-phase numerical study. *International Journal of Mechanical Sciences*, *150*, 247-264. https://doi.org/10.1016/j.ijmecsci.2018.10.037.
10. Khanafer, K., Aithal, S. M., & Vafai, K. (2019). Mixed convection heat transfer in a differentially heated cavity with two rotating cylinders. *International Journal of Thermal Sciences*, *135*, 117-132. https://doi.org/10.1016/j.ijthermalsci.2018.07.020.
11. Shirani, N., Toghraie, D., Zarringhalam, M., & Afrand, M. (2021). Numerical simulation of transient mixed convection of water–Cu nanofluid in a square cavity with multiple rotating cylinders having harmonic motion. *Journal of Thermal Analysis and Calorimetry*, *143*(6), 4229-4248. https://doi.org/10.1007/s10973-020-09379-3.

12. Barnoon, P., Toghraie, D., Salarnia, M., & Karimipour, A. (2021). Mixed thermomagnetic convection of ferrofluid in a porous cavity equipped with rotating cylinders: LTE and LTNE models. *Journal of Thermal Analysis and Calorimetry*, *146*, 187-226. https://doi.org/10.1007/s10973-020-09866-7.
13. Shirani, N., & Toghraie, D. (2021). Numerical investigation of transient mixed convection of nanofluid in a cavity with non-Darcy porous inner block and rotating cylinders with harmonic motion. *Scientific Reports*, *11*(1), 17281. https://doi.org/10.1038/s41598-021-96733-6.
14. Alshuraiaan, B. (2022). Mixed Convection Flow and Heat Transfer of Two Rotating Cylinders in a Trapezoidal Enclosure Filled with Porous Medium. *International Journal of Heat & Technology*, *40*(6). https://doi.org/ 10.18280/ijht.400619.
15. Akhter, R., Ali, M. M., Billah, M. M., & Uddin, M. N. (2023). Hybrid-nanofluid mixed convection in square cavity subjected to oriented magnetic field and multiple rotating rough cylinders. *Results in Engineering*, *18*, 101100. https://doi.org/10.1016/j.rineng.2023.101100.
16. Chatterjee, D., Gupta, S. K., & Mondal, B. (2014). Mixed convective transport in a lid-driven cavity containing a nanofluid and a rotating circular cylinder at the center. *International Communications in Heat and Mass Transfer*, *56*, 71-78. https://doi.org/10.1016/j.icheatmasstransfer.2014.06.002.
17. Selimefendigil, F., & Öztop, H. F. (2015). Mixed convection of ferrofluids in a lid driven cavity with two rotating cylinders. *Engineering Science and Technology, an International Journal*, *18*(3), 439-451. https://doi.org/10.1016/j.jestch.2015.03.003.
18. Rabbi, K. M., Shuvo, M., Kabir, R. H., Mojumder, S., & Saha, S. (2016, July). Numerical analysis of mixed convection in lid-driven cavity using non-Newtonian ferrofluid with rotating cylinder inside. In *AIP Conference Proceedings* (Vol. 1754, No. 1). AIP Publishing. https://doi.org/10.1063/1.4958376.
19. Kareem, A. K., & Gao, S. (2017). Mixed convection heat transfer of turbulent flow in a three-dimensional lid-driven cavity with a rotating cylinder. *International Journal of Heat and Mass Transfer*, *112*, 185-200. https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.118.
20. Khanafer, K., & Aithal, S. M. (2017). Mixed convection heat transfer in a lid-driven cavity with a rotating circular cylinder. *International Communications in Heat and Mass Transfer*, *86*, 131-142. https://doi.org/10.1016/j.icheatmasstransfer.2017.05.025.
21. Kareem, A. K., & Gao, S. (2018). A comparison study of mixed convection heat transfer of turbulent nanofluid flow in a three-dimensional lid-driven enclosure with a clockwise versus an anticlockwise rotating cylinder. *International Communications in Heat and Mass Transfer*, *90*, 44-55. https://doi.org/10.1016/j.icheatmasstransfer.2017.10.016.
22. Kareem, A. K., & Gao, S. (2018). Mixed convection heat transfer enhancement in a cubic lid-driven cavity containing a rotating cylinder through the introduction of artificial roughness on the heated wall. *Physics of Fluids*, *30*(2). https://doi.org/10.1063/1.5017474.
23. Mahmud, M. J., Rais, A. I., Hossain, M. R., & Saha, S. (2022). Conjugate mixed convection heat transfer with internal heat generation in a lid-driven enclosure with spinning solid cylinder. *Heliyon*, *8*(12). https://doi.org/10.1016/j.heliyon.2022.e11968.
24. Sheikhzadeh, G. A., Teimouri, H., & Mahmoodi, M. (2013). Numerical study of mixed convection of nanofluid in a concentric annulus with rotating inner cylinder. *Challenges in Nano and Micro Scale Science and Technology*, *1*(1), 26-36. https://doi.org/10.7508/tpnms.2013.01.003.
25. Selimefendigil, F., & Öztop, H. F. (2014). MHD mixed convection of nanofluid filled partially heated triangular enclosure with a rotating adiabatic cylinder. *Journal of the Taiwan Institute of Chemical Engineers*, *45*(5), 2150-2162. https://doi.org/10.1016/j.jtice.2014.06.018.

26. Wang, Y. F., Xu, X., Tian, T., Fan, L. W., Wang, W. L., & Yu, Z. T. (2015). Laminar mixed convection heat transfer of SiC-EG nanofluids in a triangular enclosure with a rotating inner cylinder: Simulations based on the measured thermal conductivity and viscosity. *J. Zhejiang Univ. Sci. A*, *16*(6), 478-490. https://doi.org/10.1631/jzus.A1400120.

27. Selimefendigil, F., & Öztop, H. F. (2015). Mixed convection in a two-sided elastic walled and SiO2 nanofluid filled cavity with internal heat generation: Effects of inner rotating cylinder and nanoparticle's shape. *Journal of Molecular Liquids*, *212*, 509-516. https://doi.org/10.1016/j.molliq.2015.09.037.

28. Selimefendigil, F., Öztop, H. F., & Abu-Hamdeh, N. (2016). Mixed convection due to rotating cylinder in an internally heated and flexible walled cavity filled with SiO2–water nanofluids: effect of nanoparticle shape. *International Communications in Heat and Mass Transfer*, *71*, 9-19. https://doi.org/10.1016/j.icheatmasstransfer.2015.12.007.

29. Alsabery, A. I., Ismael, M. A., Chamkha, A. J., & Hashim, I. (2018). Numerical investigation of mixed convection and entropy generation in a wavy-walled cavity filled with nanofluid and involving a rotating cylinder. *Entropy*, *20*(9), 664. https://doi.org/10.3390/e20090664.

30. Chamkha, A. J., & Selimefendigil, F. (2019). MHD mixed convection of nanofluid due to an inner rotating cylinder in a 3D enclosure with a phase change material. *International Journal of Numerical Methods for Heat & Fluid Flow*, *29*(10), 3559-3583. https://doi.org/10.1108/HFF-07-2018-0364.

31. Selimefendigil, F., Oztop, H. F., & Abu-Hamdeh, N. H. (2019). Mixed convection due to a rotating cylinder in a 3D corrugated cavity filled with single walled CNT-water nanofluid. *Journal of Thermal Analysis and Calorimetry*, *135*(1), 341-355. https://doi.org/10.1007/s10973-018-7068-3.

32. Selimefendigil, F., Oztop, H. F., & Chamkha, A. J. (2019). Analysis of mixed convection and entropy generation of nanofluid filled triangular enclosure with a flexible sidewall under the influence of a rotating cylinder. *Journal of Thermal Analysis and Calorimetry*, *135*, 911-923. https://doi.org/10.1007/s10973-018-7317-5,

33. Selimefendigil, F., & Öztop, H. F. (2019). Conjugate mixed convection of nanofluid in a cubic enclosure separated with a conductive plate and having an inner rotating cylinder. *International Journal of Heat and Mass Transfer*, *139*, 1000-1017. https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.053.

34. Ahmed, S. Y., Jabbar, M. Y., Hamzah, H. K., Ali, F. H., & Hussein, A. K. (2020). Mixed convection of nanofluid in a square enclosure with a hot bottom wall and a conductive half-immersed rotating circular cylinder. *Heat Transfer*, *49*(8), 4173-4203. https://doi.org/10.1002/htj.21822.

35. Ali, M. M., Akhter, R., Alim, M. A., & Miah, M. M. (2022). Magnetic-Mixed Convection in Nanofluid-Filled Cavity Containing Baffles and Rotating Hollow-Cylinders with Roughness Components. *Mathematical Problems in Engineering*, *2022*(1), 3044930. https://doi.org/10.1155/2022/3044930.

36. Alsabery, A. I., Alshukri, M. J., Jabbar, N. A., Eidan, A. A., & Hashim, I. (2022). Entropy generation and mixed convection of a nanofluid in a 3D wave tank with rotating inner cylinder. *Energies*, *16*(1), 244. https://doi.org/10.3390/en16010244.

37. Cherif, B. M., Abderrahmane, A., Saeed, A. M., Qasem, N. A., Younis, O., Marzouki, R., ... & Shah, N. A. (2022). Hydrothermal and entropy investigation of nanofluid mixed convection in triangular cavity with wavy boundary heated from below and rotating cylinders. *Nanomaterials*, *12*(9), 1469. https://doi.org/10.3390/nano12091469.

38. Abood, F. A., Yaseen, S. J., Mohammed, I. G., Homod, R. Z., & Mohammed, H. I. (2024). Enhancing thermal performance in a magnetized square cavity: novel insights from mixed

convection of Ag-MgO nanofluid around a rotating cylinder. *International Journal of Thermofluids*, *22*, 100630. https://doi.org/10.1016/j.ijft.2024.100630.

39. Misirlioglu, A. (2006). The effect of rotating cylinder on the heat transfer in a square cavity filled with porous medium. *International journal of engineering science*, *44*(18-19), 1173-1187. https://doi.org/10.1016/j.ijengsci.2006.07.008.
40. Chamkha, A. J., Selimefendigil, F., & Ismael, M. A. (2016). Mixed convection in a partially layered porous cavity with an inner rotating cylinder. *Numerical Heat Transfer, Part A: Applications*, *69*(6), 659-675. https://doi.org/10.1080/10407782.2015.1081027.
41. Malla, L. K., Jena, S. K., Mahapatra, S. K., & Chamkha, A. J. (2018). Mixed convection inside a fluid-porous composite cavity with centrally rotating cylinder. *Heat Transfer—Asian Research*, *47*(4), 684-701. https://doi.org/10.1002/htj.21336.
42. Hussein, A. K., Hamzah, H. K., Ali, F. H., & Kolsi, L. (2020). Mixed convection in a trapezoidal enclosure filled with two layers of nanofluid and porous media with a rotating circular cylinder and a sinusoidal bottom wall. *Journal of Thermal Analysis and Calorimetry*, *141*, 2061-2079. https://doi.org/10.1007/s10973-019-08963-6.
43. Abdulsahib, A. D., & Al-Farhany, K. (2020, November). Numerical Investigation of the nanofluid mixed convection on two layers enclosure with rotating cylinder: High Darcy Number Effects. In *IOP Conference Series: Materials Science and Engineering* (Vol. 928, No. 2, p. 022001). IOP Publishing. https://doi.org/10.1088/1757-899X/928/2/022001.
44. Cicek, O., Baytaş, A. F., & Baytaş, A. C. (2021). Entropy generation of mixed convection of SWCNT–water nanofluid filled an annulus with a rotating cylinder and porous lining under LTNE. *International Journal of Numerical Methods for Heat & Fluid Flow*, *31*(5), 1588-1617. https://doi.org/10.1108/HFF-04-2020-0229.
45. Ali, F. H., Hamzah, H. K., Hussein, A. K., Jabbar, M. Y., & Talebizadehsardari, P. (2020). MHD mixed convection due to a rotating circular cylinder in a trapezoidal enclosure filled with a nanofluid saturated with a porous media. *International Journal of Mechanical Sciences*, *181*, 105688. https://doi.org/10.1016/j.ijmecsci.2020.105688.
46. Al-Farhany, K., & Abdulsahib, A. D. (2021). Study of mixed convection in two layers of saturated porous medium and nanofluid with rotating circular cylinder. *Progress in Nuclear Energy*, *135*, 103723. https://doi.org/10.1016/j.pnucene.2021.103723.
47. Abderrahmane, A., Qasem, N. A., Younis, O., Marzouki, R., Mourad, A., Shah, N. A., & Chung, J. D. (2022). MHD hybrid nanofluid mixed convection heat transfer and entropy generation in a 3-D triangular porous cavity with zigzag wall and rotating cylinder. *Mathematics*, *10*(5), 769. https://doi.org/10.3390/math10050769.
48. Maneengam, A., Bouzennada, T., Abderrahmane, A., Ghachem, K., Kolsi, L., Younis, O., ... & Weera, W. (2022). Numerical study of 3D MHD mixed convection and entropy generation in trapezoidal porous enclosure filled with a hybrid nanofluid: effect of zigzag wall and spinning inner cylinder. *Nanomaterials*, *12*(12), 1974. https://doi.org/10.3390/nano12121974.
49. Rahman, M., Alim, M. A., Saha, S., & Chowdhury, M. K. (2008). Mixed convection in a vented square cavity with a heat conducting horizontal solid circular cylinder. *Journal of naval architecture and marine engineering*, *5*(2), 37-46. https://doi.org/10.3329/jname.v5i2.2504.
50. Selimefendigil, F., & Öztop, H. F. (2014). Estimation of the mixed convection heat transfer of a rotating cylinder in a vented cavity subjected to nanofluid by using generalized neural networks. *Numerical Heat Transfer, Part A: Applications*, *65*(2), 165-185. https://doi.org/10.1080/10407782.2013.826109.
51. Selimefendigil, F., & Chamkha, A. J. (2020). MHD mixed convection of nanofluid in a three-dimensional vented cavity with surface corrugation and inner rotating

cylinder. *International Journal of Numerical Methods for Heat & Fluid Flow*, *30*(4), 1637-1660. https://doi.org/10.1108/HFF-10-2018-0566.

52. Priam, S. S., Saha, R., & Saha, S. (2021, February). Pure mixed convection inside a vented square cavity with an isothermally heated rotating cylinder. In *AIP Conference Proceedings* (Vol. 2324, No. 1). AIP Publishing. https://doi.org/10.1063/5.0037533.
53. Abderrahmane, A., Alqsair, U. F., Guedri, K., Jamshed, W., Nasir, N. A. A., Majdi, H. S., ... & Marzouki, R. (2022). Analysis of mixed convection of a power-law non-Newtonian nanofluid through a vented enclosure with rotating cylinder under magnetic field. *Annals of Nuclear Energy*, *178*, 109339. https://doi.org/10.1016/j.anucene.2022.109339.
54. Costa, V. A. F., & Raimundo, A. M. (2010). Steady mixed convection in a differentially heated square enclosure with an active rotating circular cylinder. *International Journal of Heat and Mass Transfer*, *53*(5-6), 1208-1219. https://doi.org/10.1016/j.ijheatmasstransfer.2009.10.007.
55. Khan, M., Khan, A. A., & Hasan, M. N. (2016, July). Numerical study of mixed convection heat transfer from a rotating cylinder inside a trapezoidal enclosure. In *AIP Conference Proceedings* (Vol. 1754, No. 1). AIP Publishing. https://doi.org/10.1063/1.4958427.
56. Nair, Y., Shakkottai, V., & Prasad, B. V. S. S. S. (2016, July). Mixed convection heat transfer in an annulus with rotating inner cylinder. In *Heat Transfer Summer Conference* (Vol. 50336, p. V002T15A004). American Society of Mechanical Engineers. https://doi.org/10.1115/HT2016-7148.
57. Alam, M., Kamruzzaman, K., Ahsan, F., & Hasan, M. N. (2016, July). Mixed convection heat transfer inside a differentially heated square enclosure in presence of a rotating heat conducting cylinder. In *AIP Conference Proceedings* (Vol. 1754, No. 1). AIP Publishing. https://doi.org/10.1063/1.4958426.
58. Selimefendigil, F., & Öztop, H. F. (2016). MHD mixed convection and entropy generation of power law fluids in a cavity with a partial heater under the effect of a rotating cylinder. *International Journal of Heat and Mass Transfer*, *98*, 40-51. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.092.
59. Alam, M., Kamruzzaman, K., Saha, S., & Hasan, M. N. (2017, June). Effect of location of a rotating circular cylinder and heat source on mixed convection heat transfer characteristics inside a square enclosure with discrete heater at the bottom wall. In *AIP Conference Proceedings* (Vol. 1851, No. 1). AIP Publishing. https://doi.org/10.1063/1.4984730.
60. Shahriar, M., & Mamun, M. A. H. (2019, July). Magnetic field effect on mixed convection in ferrofluid filled c-shaped cavity with rotating circular cylinder at different positions with intruded heated sides. In *AIP Conference Proceedings* (Vol. 2121, No. 1). AIP Publishing. https://doi.org/10.1063/1.5115920.
61. Selimefendigil, F., & Öztop, H. F. (2020). Mixed convection in a PCM filled cavity under the influence of a rotating cylinder. *Solar Energy*, *200*, 61-75. https://doi.org/10.1016/j.solener.2019.05.062.
62. Azim, E., Sagor, M. J. H., Hasan, A. B. M. R., & Saha, S. (2021, February). Investigation on conjugate mixed convection inside a square cavity with heat generating rotating circular cylinder. In *AIP Conference Proceedings* (Vol. 2324, No. 1). AIP Publishing. https://doi.org/10.1063/5.0037524.
63. Mohammed, A. (2021). Natural convection heat transfer inside horizontal circular enclosure with triangular cylinder at different angles of inclination. *Journal of Thermal Engineering*, *7*(1), 240-254. https://doi.org/10.18186/thermal.849812.