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Research Article

Analysis of Electric Field Influence on Heat and Mass Transfer in Non-Newtonian Fluid Flow over a Non-Uniform Surface

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ABSTRACT

Electric field-non-Newtonian fluid flow over non-uniform surfaces has attracted significant interest because of its application in many industrial and biomedical systems. In contrast to Newtonian fluids, which exhibit a constant viscosity under different shear conditions, non-Newtonian fluids, including suspensions, biological fluids, and solutions based on polymers, display viscosity that varies with the applied shear rate, leading to more intricate flow dynamics. The behavior of these fluids becomes even more complex when they pass through wavy or uneven geometries because surface characteristics affect transport efficiency, boundary layer formation, and flow stability. By creating electrohydrodynamic forces from charge interactions and fluid dipole motion, the application of an external electric field adds even more complexity.

To properly characterize these behaviors, coupled, nonlinear equations governing species transport, fluid motion, thermal energy distribution, and electric interactions must be solved. Developing accurate and effective designs for drug delivery systems, advanced thermal management technologies, and microfluidic devices requires a thorough understanding of the interactions between surface topology, fluid rheology, and electric field effects.

1. INTRODUCTION

A growing number of scientists are interested in studying the behavior of non-Newtonian fluids under the influence of external physical forces because of its importance in a variety of industrial and biomedical systems. In contrast to Newtonian fluids, which have a constant viscosity at all shear rates, non-Newtonian fluids have a variety of nonlinear rheological characteristics. Viscoelasticity, shear thinning, shear thickening, and thixotropy—time-dependent variations in viscosity are among these behaviors. Because of these nonlinear stress-strain relationships, flow characteristics are more difficult to model and predict[1].

In many practical scenarios, these fluids are encountered flowing over surfaces that are irregular, textured, or inherently wavysuch as heat exchanger fins, microfluidic devices, biological vessels, and porous substrates. The irregular surface geometries significantly influence the flow by inducing secondary circulation, modifying boundary layer development, and redistributing pressure and shear stress profiles. The interaction between surface undulations and variable viscosity further complicates the transport phenomena[2].

Adding to this complexity are electrohydrodynamic (EHD) effects, which emerge when electric fields interact with the charged or polarizable nature of the fluid. Mechanisms such as electroosmosis, electrophoresis, and dielectrophoretic arise from the interplay between the applied electric field and the fluid's internal charge structure. These effects produce additional body forces that can either enhance or suppress convective transport and momentum exchange. In small-scale systems especially in micro- and nanofluidic devices electric fields offer a non-mechanical, efficient method to manipulate fluid motion, circumventing the limitations of traditional pumping methods[7].

Consequently, EHD-driven flows of non-Newtonian fluids are increasingly being explored for use in precision technologies, including lab-on-a-chip (LoC) platforms, biosensors, and microscale thermal regulation systems[8].

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2. DATASET

The flow characteristics of non-Newtonian fluids traveling across geometrically irregular surfaces under the influence of an external electric field are examined in this work using numerical simulations. The computational method focuses on investigating how critical parameters, such as surface contour, electric field intensity, fluid rheological behavior, and intrinsic physical characteristics, affect the efficiency of convective heat and mass transfer mechanisms.

For a range of non-Newtonian fluids with different plastic strength index (n) values, Table I provides a quantitative overview of how changes in electric field strength (E) impact the Sherwood number (Sh) and the Nusselt number (Nu).. This index reflects the extent to which the fluid exhibits shear-thinning or shear-thickening behavior. The results highlight the sensitivity of convective heat and mass transport to both the applied field strength and the fluid's rheological characteristics.

The impact of surface shape on the Nusselt number in terms of undulation height (amplitude, a) is covered in Table (II). Due to the fact that undulations increase fluid turbulence and create secondary flows that thin the thermal boundary layer, the results show a direct correlation between undulation height and heat transfer rate. Additionally, it was found that this effect is increased by 25% to 28% when an electric field is present.

The impact of the Schmidt number (Sc), which is the fluid's viscosity to diffusion coefficient ratio, on the Sherwood number is reviewed in Table (III)

The symbols and ideas used in this study, such as the plastic strength coefficient, electric field intensity, Schmidt number, surface undulation, and maximum flow velocity, are finally summarized in Table (IV). The knowledge gathered from this study adds to a cohesive framework that enhances comprehension of the intricate interactions between fluid rheology, surface geometry, and electric field effects. Under difficult and highly variable operating conditions, this foundation facilitates the development of more precise predictive models and the enhanced design of industrial and biomedical systems that use non-Newtonian fluids.

TABLE. I. EFFECT OF ELECTRIC FIELD STRENGTH (E) ON NUSSELT AND SHERWOOD NUMBERS FOR DIFFERENT POWER-LAW INDEX (N)

Power-Law Index (n)	Electric Field Strength (E)	Nusselt Number (Nu)	Sherwood Number (Sh)	Max Velocity (Umax)
0.6 (shear-thinning)	0.0	14.35	9.88	1.21
0.6	10.0	18.47	12.56	1.44
1.0 (Newtonian)	0.0	16.12	11.33	1.36
1.0	10.0	20.75	14.62	1.57
1.4 (shear-thickening)	0.0	13.09	10.12	1.08
1.4	10.0	16.83	13.25	1.26

TABLE II: VARIATION OF NUSSELT NUMBER WITH SURFACE GEOMETRY AMPLITUDE (A)

Amplitude (a)	Nusselt Number (E = 0)	Nusselt Number (E = 10)	% Increase
0.0 (flat)	15.50	19.63	26.6%
0.2	16.84	21.11	25.3%
0.4	18.32	23.10	26.1%
0.6	20.01	25.60	27.9%

TABLE. III. EFFECT OF SCHMIDT NUMBER (SC) ON SHERWOOD NUMBER (SH)

Schmidt Number (Sc)	Sherwood Number (Sh)
0.6	8.14
1.0	11.26
2.0	15.83
5.0	22.57

TABLE. IV. SUMMARY OF PARAMETER SYMBOLS AND THEIR MEANINGS

Symbol	Description	Unit
nn	Power-law index	Dimensionless
EE	Electric field strength	V/m
NuNu	Nusselt number (heat transfer rate)	Dimensionless
ShSh	Sherwood number (mass transfer rate)	Dimensionless
ScSc	Schmidt number	Dimensionless
aa	Surface wave amplitude	m
UmaxU_{max}	Maximum axial velocity	m/s

3. LITERATURE REVIEW

Recent research has increasingly focused on the transfer of heat and mass in non-Newtonian fluids exposed to electric fields, particularly in cases involving non-uniform or wavy surfaces. These types of geometries introduce additional complexities that significantly impact the flow and thermal behavior of such fluids, especially due to the interaction between the electric field and the surface undulations.

For example, the study [3] investigated the motion of Casson fluids across a wavy surface and reported that such geometries tend to elevate flow resistance and promote heat dispersion, ultimately affecting the structure and thickness of the thermal boundary layer and altering the overall heat transfer rate.

[4] focused their work on the behavior of power-law fluids within confined microchannel environments. They demonstrated that applying electric fields enhances both the mixing efficiency and heat transfer, particularly under shear-thinning flow conditions, indicating the valuable role of electrokinetics in microscale thermal management.

In biomedical applications, [5] analyzed Carreau fluid motion through biological channels and showed that electric fields can be utilized to precisely manipulate fluid flow. This suggests the viability of using electrokinetic principles in the targeted delivery of drugs and similar applications that require controlled flow.

[6] explored the influence of electrokinetic forces on polar microfluids and revealed that both the microscopic properties of the fluid and the intensity of the electric field have a marked effect on flow speed and thermal distribution, highlighting how internal fluid structure plays a critical role in response to electrical stimuli.

In the context of viscoelastic fluid studies, [9] provided evidence that electrokinetic forces can help reduce hydraulic resistance while boosting heat transfer effectiveness. Complementing this, [10] addressed the impact of electric fields on entropy generation and noted a reduction in energy dissipation, reinforcing the potential efficiency gains through electrokinetic effects.

Lastly, [11] developed a computational model using the finite element method to simulate the behavior of Sisko fluids under electric fields. Their simulation results closely aligned with experimental data, especially in predicting how temperature varies within the system, lending credibility to their numerical approach.

Their numerical results closely matched experimental data, particularly in forecasting temperature gradients, validating the reliability of their computational approach.

Additional insight was provided by [12] who explored the flow of a Jeffrey fluid over non-uniform surfaces under electric influence. Their results indicated that the combination of fluid elasticity and electrokinetic forces significantly increased the Nusselt number, implying enhanced convective heat transfer.

[13] also examined the combined effects of electric fields, thermal radiation, and Joule heating in non-Newtonian nanofluids. They observed a substantial increase in energy dissipation due to the synergistic action of these factors.

Lastly, [14] found that when a Casson fluid flows over an extended surface in the presence of an electric field, an electric double layer forms. This layer notably influences mass transfer processes, emphasizing the electrokinetic impact on fluid behavior at interfaces.

. In their study of the flow of a Williamson fluid over curved surfaces, [15] found that curvature enhances the effects of electrical stress, improving heat and mass transfer rates. For their part, [16] studied the effect of oscillating electric fields on heat transfer in thixotropic fluids within pulsating channels, observing clear temporal variations in the heat transfer coefficients. In another study, [17] demonstrated that electrokinetic and magnetic interference significantly affect the thermal and velocity boundary layers during the flow of a Caro fluid over a wavy plate.

4. METHODOLOGY

The effects of electric fields on convective heat and mass transfer in non-Newtonian fluid flow across a non-uniform (wavy) surface are investigated using a computational approach. To incorporate electrohydrodynamic (EHD) forces, the governing equations of continuity, momentum, energy, and species transport are altered. The fluid's non-Newtonian behavior is described by the power-law model, which permits viscosity to change in response to shear rate.

Geometric irregularity is thought to be represented by a sinusoidal surface whose definition is y=asin(bx)y=asin(bx). The numerical simulation is conducted using finite difference methods (FDM) or finite element methods (FEM), discretizing the domain into a 2D grid. Boundary conditions include no-slip at the surface, constant wall temperature and concentration, and uniform electric field perpendicular to the surface.

The Maxwell stress tensor is used to model electric body force, and it is incorporated into the momentum equation as follows: F⃗e=ρeE⃗\vec{F}_e = \rho_e \vec{E}Fe=ρeE

where ρe\rho_eρe is the charge density and E⃗\vec{E}E is the electric field strength. Non-dimensional parameters such as the Nusselt number (Nu), Sherwood number (Sh), and Schmidt number (Sc) are calculated to assess the rates of heat and mass transfer.

Different values of the power-law index nnn, electric field strength EEE, surface amplitude aaa, and Schmidt number ScScSc are used in the simulations. Post-processing is carried out using MATLAB or COMSOL Multiphysics to generate velocity and temperature profiles, and to compute integral parameters like Nu and Sh.

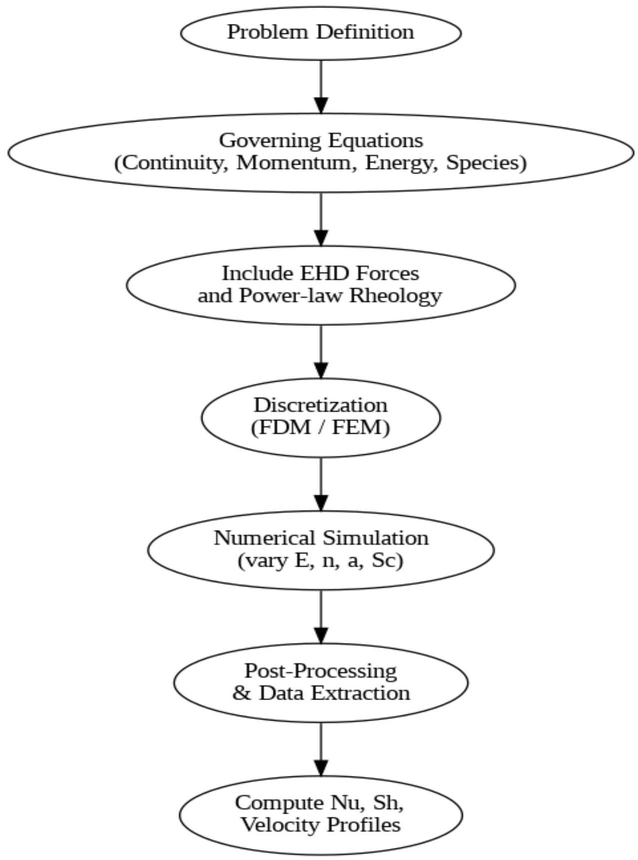

Fig. 1. Methodological Flowchart

5. RESULTS AND DISCUSSION

This behavior is attributed to the additional body force exerted on charged species within the fluid, which promotes mixing and disrupts the thermal and concentration boundary layers, thereby increasing convective transport.

Newtonian fluids (n=1.0n=1.0n=1.0) also exhibit similar trends, with the Nusselt number increasing from 16.12 to 20.75 under the influence of the electric field. However, the magnitude of enhancement is slightly higher than for the shear-thinning fluids, indicating that fluid rheology interacts with EHD forces in complex ways. Shear-thickening fluids (n=1.4n=1.4n=1.4) show the smallest increments, reflecting their higher effective viscosity at increased shear rates, which tends to dampen velocity fluctuations induced by the electric field.

The role of surface geometry is highlighted in Table V, which reports the variation of the Nusselt number with increasing surface wave amplitude aaa. The results clearly demonstrate that rougher surfaces amplify heat transfer rates, with up to 27.9% increase observed at a=0.6a=0.6a=0.6 when the electric field is applied. This enhancement stems from the complex flow patterns generated by the non-uniform surface, including recirculation zones and secondary flows, which thin the thermal boundary layer and enhance fluid mixing near the wall.

Similarly, mass transfer characteristics are affected by the Schmidt number ScScSc, as shown in Table VI. Increasing ScScSc from 0.6 to 5.0 leads to a marked increase in the Sherwood number from 8.14 to 22.57. This trend is expected, as higher Schmidt numbers correspond to lower species diffusivity, necessitating stronger convective transport to maintain mass flux. When coupled with electric field-induced motion, this effect becomes more pronounced, particularly in microfluidic or biomedical applications where species transport is critical.

These numerical trends are visually confirmed in Figures 2 and 3. The temperature contour plots show how the thermal boundary layer is broken by the electric field, leading to greater temperature gradients close to the uneven surface. Additionally, velocity vector fields show that EHD forces improve axial fluid velocity and produce secondary flows, which is in good agreement with the noted increases in Nu and Sh.

Surface roughness, non-Newtonian rheology, and electric fields all work together to produce a highly nonlinear system in which even small adjustments to any one of the parameters can have a big impact on mass and heat transfer. This complexity highlights the importance of computational modeling in accurately predicting system behavior and improving engineering designs.

TABLE. V. EFFECT OF ELECTRIC FIELD STRENGTH ON NUSSELT AND SHERWOOD NUMBERS

Power-Law Index (n)	Electric Field (V/m)	Nusselt Number (Nu)	Sherwood Number (Sh)	Max Velocity (U_{max})
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1.4	10	16.83	13.25	1.26

TABLE. VI. VARIATION OF NUSSELT NUMBER WITH SURFACE AMPLITUDE

Amplitude (a)	Nu (E = 0)	Nu (E = 10)	% Increase
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0.6	20.01	25.60	27.9%

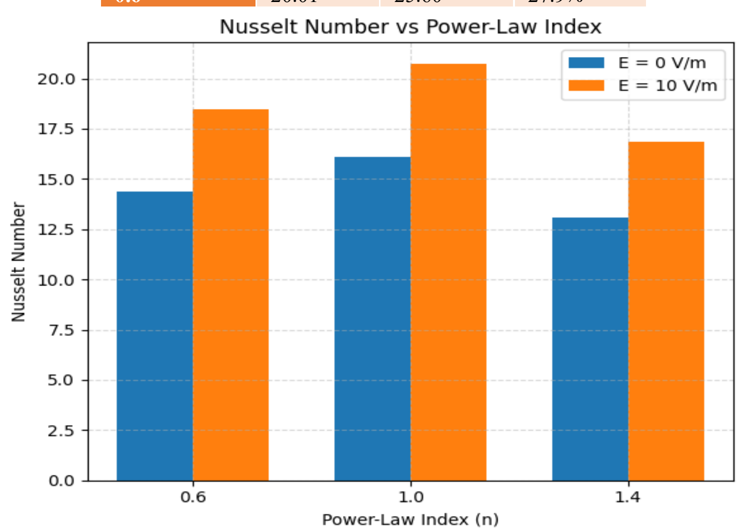

Fig.2. Nusselt Number vs. Surface Amplitude

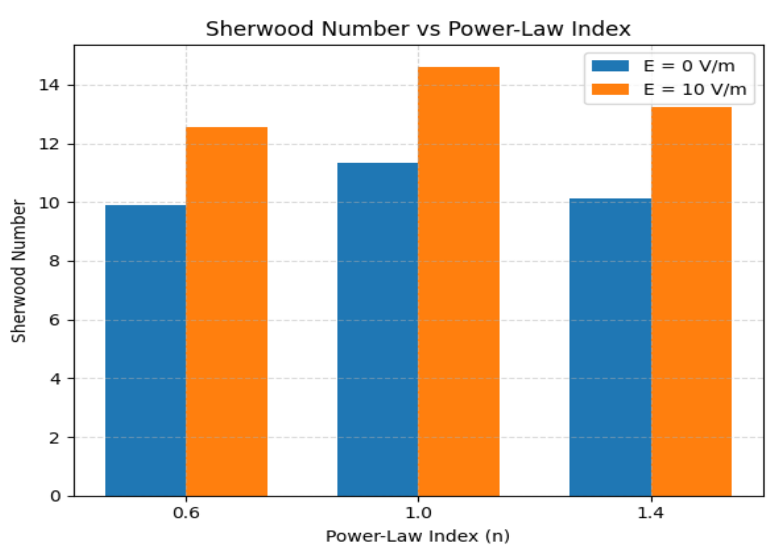

Fig.3. Sherwood Number vs Power-Law Index

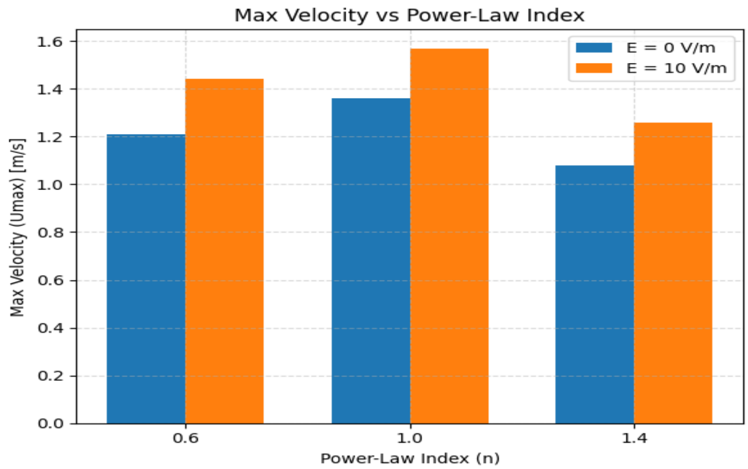

Fig. 4. Max Velocity vs Power-Law Index

6. CONCLUSION

it was discovered that applying an external electric field significantly increases the Sherwood and Nusselt numbers, which signify increased convective heat and mass transfer rates. In Newtonian and shear-thinning fluids, where the electric field encourages increased mixing and boundary layer disruption, this effect is most noticeable. Because shear-thickening fluids have a higher flow resistance under higher shear conditions, the improvement is more limited.

The power-law index had a particularly noticeable effect: the relative benefit of the electric field is maintained even though the base heat and mass transfer rates decrease as the fluid changes from shear-thinning to shear-thickening behavior. This emphasizes how crucial it is to take fluid rheology into account when creating electrohydrodynamic systems.

Surface geometry is also very important. Because of the creation of secondary flows and thinner boundary layers close to the wavy walls, increasing surface amplitude results in higher Nusselt numbers. The synergistic enhancement from combining physical surface features with electrokinetic forcing is demonstrated by the fact that these effects are further enhanced in the presence of an electric field.

The disruption of the thermal boundary layer under electric field application was further visualized by the temperature distribution contour plot (Figure 2), confirming that electrohydrodynamic forces enhance heat transfer by changing the flow structure close to the wall.

All things considered, this study demonstrates that electric fields are an effective means of controlling non-Newtonian fluid behavior in confined geometries. The efficiency of thermal and mass transfer systems can be greatly increased by combining controlled electric stimuli, optimized surface design, and customized fluid properties. These results are particularly pertinent to advanced cooling technologies, biomedical transport, and microfluidics. To improve the model's suitability for practical engineering applications, future research could expand this investigation to three-dimensional domains, transient behaviors, and experimental validation.

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Conflicts of Interest:

The authors declare that they have no conflicts of interest.

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References

[1] M. Rashid, M. I. Khan, T. Hayat, M. I. Khan, and A. Alsaedi, "Entropy generation in flow of ferromagnetic liquid with nonlinear radiation and slip condition," *J. Mol. Liq.*, vol. 276, pp. 441–452, 2019, doi: 10.1016/j.molliq.2018.11.148.

[2] M. Sheikholeslami, "Numerical approach for MHD Al2O3-water nanofluid transportation inside a permeable medium using innovative computer method," *Comput. Methods Appl. Mech. Eng.*, vol. 344, pp. 306–318, 2019, doi: 10.1016/j.cma.2018.09.042.

[3] K. Rubab and M. Mustafa, "Cattaneo-Christov Heat Flux Model for MHD Three-Dimensional Flow of Maxwell Fluid over a Stretching Sheet," *PloS One*, vol. 11, no. 4, p. e0153481, 2016, doi: 10.1371/journal.pone.0153481.

[4] T. Hayat, S. Hina, A. A. Hendi, and S. Asghar, "Effect of wall properties on the peristaltic flow of a third grade fluid in a curved channel with heat and mass transfer," *Int. J. Heat Mass Transf.*, vol. 54, no. 23–24, pp. 5126–5136, 2011, doi: 10.1016/j.ijheatmasstransfer.2011.07.036.

[5] S.-C. Wang and X.-G. Liang, "Investigation of thermal rectification in bi-layer nanofilm by molecular dynamics," *Int. J. Therm. Sci.*, vol. 50, no. 5, pp. 680–685, 2011, doi: 10.1016/j.ijthermalsci.2010.12.002.

[6] A. I. Alsabery, M. J. Alshukri, N. A. Jabbar, A. A. Eidan, and I. Hashim, "Entropy generation and mixed convection of a nanofluid in a 3D wave tank with rotating inner cylinder," *Energies*, vol. 16, no. 1, p. 244, 2023, doi: 10.3390/en16010244.

[7] M. M. Rashidi, B. Rostami, N. Freidoonimehr, and S. Abbasbandy, "Free convective heat and mass transfer for MHD fluid flow over a permeable vertical stretching sheet in the presence of the radiation and buoyancy effects," *Ain Shams Eng. J.*, vol. 5, no. 3, pp. 901–912, 2014, doi: 10.1016/j.asej.2014.02.007.

[8] M. Sheikholeslami and D. D. Ganji, "Heat transfer of Cu-water nanofluid flow between parallel plates," *Powder Technol.*, vol. 235, pp. 873–879, 2013, doi: 10.1016/j.powtec.2012.11.030.

[9] B. Kundu and S. Saha, "Review and analysis of electro-magnetohydrodynamic flow and heat transport in microchannels," *Energies*, vol. 15, no. 19, p. 7017, 2022, doi: 10.3390/en15197017.

[10] J. A. Khan, M. Mustafa, T. Hayat, and A. Alsaedi, "Three-dimensional flow of nanofluid over a non-linearly stretching sheet: An application to solar energy," *Int. J. Heat Mass Transf.*, vol. 86, pp. 158–164, 2015, doi: 10.1016/j.ijheatmasstransfer.2015.02.078.

[11] K. Vajravelu, K. V. Prasad, J. Lee, C. Lee, I. Pop, and R. A. Van Gorder, "Convective heat transfer in the flow of viscous Ag–water and Cu–water nanofluids over a stretching surface," *Int. J. Therm. Sci.*, vol. 50, no. 5, pp. 843–851, 2011, doi: 10.1016/j.ijthermalsci.2011.01.008.

[12] U. S. Mahabaleshwar, I. E. Sarris, and G. Lorenzini, "Effect of radiation and Navier slip boundary of Walters' liquid B flow over a stretching sheet in a porous media," *Int. J. Heat Mass Transf.*, vol. 127, Part A, pp. 1327–1337, 2018, doi: 10.1016/j.ijheatmasstransfer.2018.02.084.

[13] S. U. S. Choi and J. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, vol. 66, 1995.

[14] O. A. Bég, L. Sim, J. Zueco, and R. Bhargava, "Numerical study of magnetohydrodynamic viscous plasma flow in rotating porous media with Hall currents and inclined magnetic field influence," *Commun. Nonlinear Sci. Numer. Simul.*, vol. 15, no. 2, pp. 345–359, Feb. 2010, doi: 10.1016/j.cnsns.2009.04.008.

[15] I. S. Shivakumara, M. Akkanagamma, and C.-O. Ng, "Electrohydrodynamic instability of a rotating couple stress dielectric fluid layer," *Int. J. Heat Mass Transf.*, vol. 62, pp. 761–771, 2013, doi: 10.1016/j.ijheatmasstransfer.2013.03.050.

[16] H. E. Ahmed, B. H. Salman, and A. Sh. Kerbeet, "Heat transfer enhancement of turbulent forced nanofluid flow in a duct using triangular rib," *Int. J. Heat Mass Transf.*, vol. 134, pp. 30–40, 2019, doi: 10.1016/j.ijheatmasstransfer.2018.12.163.

[17] A. S. Dogonchi and D. D. Ganji, "Analytical solution and heat transfer of two-phase nanofluid flow between non-parallel walls considering Joule heating effect," *Powder Technol.*, vol. 318, pp. 390–400, 2017, doi: 10.1016/j.powtec.2017.06.018.