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Analytical study on heat transfer addition of different nano liquids in vertical rotating system with CFD

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Abstract:

This study presents an analytical investigation into the heat transfer performance of various nanofluids—namely copper oxide (CuO), aluminum oxide (Al_2O_3), and zinc oxide (ZnO) dispersed in water—within a vertical rotating system. The relationship between the system's thermal and flow properties and the type of nanoparticle, volume percent, and rotating speed is investigated in the analysis. The boundary layer theory and similarity transformations are used to convert the governing partial differential equations into a set of nonlinear ordinary differential equations. Then, the equations are solved numerically. The results demonstrate that compared to the base fluid, heat transmission is significantly enhanced with the inclusion of nanoparticles. The thermal conductivity is highest in nanofluids comprising CuO and water, then in nanofluids containing Al_2O_3 and ZnO. Also, the thermal boundary layer and flow velocity are both significantly affected by the rotational motion. Thermal management of rotating machinery and industrial processes can benefit from the study's emphasis on nanofluids' ability to optimize heat exchange in rotating systems.

Keywords: vertical rotating system, heat transfer, nano liquids

1.Introduction

When introduced into a vertical rotating system, the interaction between centrifugal forces, Coriolis effects, and thermal gradients leads to complex flow behaviors that strongly influence heat transfer. In such configurations, conventional fluids often fail to maintain optimal thermal performance due to limited thermal conductivity and non-uniform temperature distribution. To address this challenge, nanofluids offer a promising solution. Convective heat transfer is improved by dispersing nanoparticles, which modifies flow dynamics and increases effective thermal conductivity. Nonetheless, because to variations in density, specific heat, and thermal characteristics, the performance differs substantially across nanoparticle types. Over the past 20 years, researchers have studied nanofluid flow on a vertical plate, which has shed light on the material's significance in real-world applications. Choi came up with a novel heat transfer fluid called a nanofluid. It incorporates a base liquid with solid nanoparticles floating in it. The particles increase the convectional heat coefficient and thermal conductivity compared to the root fluid. to assessed nanofluid thermal conductivity and put out a model involving Brownian diffusion and thermophoresis. In most cases, nanofluids vastly improve the heat transfer rate by boosting the overall performance of thermal systems. Hydrogen, chlorohydric acid, or oil is the core fluid of a nanofluid, which may also contain carbon, metal oxides, and other nanoparticles. In metals (Ag, Cu, Au, Fe), metallic oxides (Al2O3, TiO2, SiO2, ZrO2), and carbon (diamond, graphite, CNT), nanoparticles are employed often. As a means of reducing heat resistance, nanofluids are widely used in the electronics and automotive industries. Radiators, cooling systems, and heat transfer equipment rely on them as coolants because of how well they function. Electrical equipment and radiators mostly utilize next-generation fluids as a cooling agent due to their remarkable thermal qualities. Nanofluid improves the thermal conductivity, viscosity, specific heat, and density of a base fluid when added to it. Theoretical and practical considerations of nanofluid production, fluid viscosity and thermal conductivity, and other related topics were treated in detail. The study also found that novel fluids derived from metal oxide nanoparticles have certain interesting physical features, which bode well for their potential use in industrial systems that handle high temperatures. Several scientists were interested in the nanofluids because of the improved heat transfer they exhibited. Transcalency is one of the engineered fluids' adjustable qualities that may be achieved by changing the particle concentration. Nanofluid flows over vertical plates have recently shown more noticeable heat and mass convection transmission.

2.Literature review

Gamal El-Din A. Azzam [1] Investigated the impact of radiation on MHD According to computational solutions of the governing equations of convective stable laminar boundary layer flow, a uniform magnetic field and considerable temperature variations can create a partially correct distribution of velocities. The impact of viscous dissipation on boundary layer flow on a vertical plate was studied by E. Magyari and D.A.S. Rees [2]. Upflow is possible for self-similar flows up to a critical number, whereas downflow is possible for any non-negative value of the temperature exponent. This article explores the heat characteristics of free convection flows from both an analytical and numerical perspective. C.J.Toki [3] studied the free convection mass transfer process on a vertical porous plate; the findings revealed that the non-porous plate had lower temperatures and velocities near the porous plate; the study also yielded an analytical solution; and subsequent publication of the results prompted additional investigation into vertical air flows into the atmosphere. C.J.Toki [4] investigates the unstable flow on a porous plate that oscillates vertically; in this instance, the author considered a fluid that is both viscous and incompressible; analytical solutions were derived for arbitrary Prandtl numbers for the governing equations. O.D. Makinde et al. [5] [] developed the governing equations after carefully studying the effect of thermal buoyancy on the boundary layer around a vertical plate. Over the whole plate, a smaller thermal boundary layer is produced by increasing the Prandtl and Grashof numbers. Within a mixed-hypertensive (MHD) zone of influence, W.A. Khan et al [6] study the Navier-Slip flow of a nanofluid including gyrotactic microbes across a vertical plate. Using similarity transformation, which mitigates the impact of Brownian motion as well as thermophoresis in the Navier slip condition, these writers discovered similarity solutions for dimensional-less variables. Adding the factor of viscous dissipation to the energy equation. Meraj Mustafa et al. [7] performed numerical calculations of the velocity and temperature profiles and investigated the effect of nonlinear radiation heat transfer on nanofluids passing through a vertical plate. D. Srinivasacharya et al [8] discovered numerical solutions by investigating the impact of two stratification layers on the flow of nanofluids submerged in porous medium over a vertical plate. The authors' model involved a decrease in heat transmission due to the Brownian motion variable and the heat transfer effect. M. Ghalambaz et al. [9] studied the effect of a porous medium on the nanofluid flow on a vertically heated panel. The numerical solution is presented in the publication. The temperature gradient becomes steeper and the concentration profile becomes flatter as the Brownian motion parameter gets more significant. "Ganaeswara Reddy Machireddy" Integrated Brownian motion and thermophoresis into our computational model of the upcoming development of fluid convection boundary layer flow [10]. The data shows that when the Prandtl number grows, the temperature decreases and the lowered Nusselt number gets less. Free convection flow across a moving vertical plate was studied by them, as was fractional nanofluid behavior. Ali Azhar et al. [11] computationally resolved the controlling equations by means of the Laplace transform technique. In comparison to regular fluids, fractional nanofluids have a much smaller thermal boundary layer, according to their findings. Marneni Narahari et al. [12] The findings corroborated the connections when the local Nusselt values were double-checked. Given the activation energy and the results of binary chemical reactions on vertical plates, S.Anuradha and M. Yegammai [13] created a two-dimensional model to assess multi-layer multi-layer hydrodynamic flow (MHD) in nanofluids, and then used numerical methods to solve the corresponding equations. Wafula Maurine Maraca [14] used the Similarity Solution method to study nanofluid interface flow. This study presents numerical solutions to the boundary value issue and shows that when the unsteadiness parameter grows, the flow direction and velocity of nanofluids decrease. Marneni Narahari [15] employs a crank Nicolson numerical framework; the paper's findings are supported by the correlation results. In their study, Abdul Rauf and Yasir Mahsud [16] examined the two-dimensional flux on nanofluids as a function of time and exponential temperature. A modified version of the simple function technique was used to solve the governing equations. This study will lay the groundwork for carrying out numerical calculations. The relationship between thermal radiation, nanofluid internal heat generation, and convection movement in a porous media was investigated by Hiranmony et al. [17]. Writers used numerical methods to solve the governing equations. Various physical properties are examined in the article by examining the effects of boundary conditions. Zecheng and jiepeng [18] These results emphasize the crucial importance of this process; the authors used the IBL approach to get results from their inquiry into nanofluids using wavy films, with an emphasis on nano particle migration. Aamir Hamad et al. [19] investigated the radiative Williamson nanofluid's Blasius flow across an inclined plane caused by multi-layer shear. Chebbi Agnes Jeptoo [20] investigated the top-heat-flow (MHD) of nanofluid generated by gyrotactic microorganisms via a vertically heated plate. The effects of magnetic fields on the flow, heat transfer, and mass transfer in nanofluid boundary layers were investigated using computational models. M Veera Krishna and Ali J Chamka [21] investigated the impact of Hall and Slip on MHD A nanofluid is pushed through a porous substance trapped within two vertical plates using centrifugal force. Using the Dufour parameters and radiation absorption, this research demonstrates that the thermal boundary layer increases. Elbashbeshy, E.M.A et al [22] A vertically extended surface, embedded in a porous medium with gyrotactic microorganisms, allows the nanofluid's boundary layer to pass across In spite of the surface's increasing temperature, a nonlinear velocity is pulling it apart. Wan Nura'in Nabilah Noranuar et al [23] The fluid flow and heat transmission on MHD Casson nanofluid are investigated in this work as a function of time while a non-coaxially rotating disk passes through a porous material. As far as nanoparticles are concerned, human Casson blood contains a combination of single- and multi-walled carbon nanotubes. Kamel, R.S., Ismaeel [24] Also studied were the effects of heat radiation, tissue heat absorption coefficient, nanofluid interstitial liquid velocity, and heat transmission inside tumor tissue. Balreddy et al [25], In this investigation, the impact of radiation, rotation, and Hall current on the mass and heat transfer free convection flow of an impermeable, viscous, electrically conducting fluid embedded in a porous material that produces heat is investigated over an infinite vertical. Patel et al. [26] developed nanofluids using gold and silver for the very first time. Transient hot wire method was also employed for the purpose of determining thermal conductivity. An obvious increase in heat conductivity for very low levels was the most crucial finding of their investigation. Xie et al. [27] studied how changes to the base fluid affected the heat conductivity of fluid-nanoparticle mixtures. The scientists looked at α-Al2O3 in nanoparticle form combined with various substances including deionized water, glycerol, ethylene glycol, pump oil, ethylene glycol-water, and glycerol-water combinations. Yu et al. [28] have demonstrated that particle collisions with drift velocities can explain a negligible fraction of the improvement. Their work demonstrated, using copper particles in ethylene glycol as an example, that the presence of nano-convection in the interparticle space allows one to predict the magnitude of the enhancement. Recently, Patel et al. [29] have used a novel semiempirical method to empirically model nanofluid thermal conductivity. An increase in the specific surface area and micro-convection based on Brownian motion are responsible for the high improvements. Bhattacharya et al. [30] Simulating the behavior of nanofluids under Brownian motion also helped to establish their effective conductivity. Both the Cu-ethylene glycol and Al2O3-ethylene glycol simulation results were within 3% of the experimental data, respectively. Recently, Xuan and Yao [31] created a Lattice Boltzmann model to study the distribution and flow pattern of nanoparticles and discovered that increasing the fluid's temperature and main flow can increase the distribution of nanoparticles, which is good for improving the nanofluids' energy transport. Choi et al. [32] realized that the discrepancy may be due to the fact that the fluids in issue may include acids or bases, rendering the electrostatic repulsion approach unsuitable for them. The fact remained, nonetheless, that shear rate was completely uncorrelated with viscosity. The concentration-dependent decrease of the natural convective heat transfer coefficient was shown to be mediated by the nanofluids. Findings differ from numerical simulation for nanofluids' natural convective heat transfer behavior in a two-dimensional horizontal container by Khanafer et al. [33]. Nevertheless, the findings from the experiment are in agreement with what Putra et al. [34] found: a reduced natural convective heat transfer coefficient for aqueous CuO and Al2O3 nanofluids within a horizontal cylinder. The researchers blamed particle/fluid slide and nanoparticle sedimentation for the drop. As a possible explanation for the decline in heat transfer, the authors speculate on convection caused by concentration differences, interactions between particles and surfaces, and changes to the dispersion properties. Ahmed, W **[35]** Using a first-order chemical reaction on a semi-infinite vertically rotating plate submerged in a porous media, a numerical study of an unstable free convection of MHD nanofluid flow was carried out. There is an assumption in the mathematical model of the fluid's flow that its viscosity changes as a function of temperature. P. Pramod Kumar et al **[36]** This study presents a mathematical model that delineates the radially expanding axisymmetric discharge of an electrically conductive fluid over a surface, taking into account the effects of the Soret number. The dynamics of the flow are examined as the surface experiences exponential radial expansion. Chatla Mangamma et al **[37]** To measure the Dufour number effects on the flow patterns and heat transfer in an exponentially accelerated infinite vertical plate embedded in a porous medium in the presence of heat source and chemical reaction. Bala Siddhulu Malga et al **[38]** A numerical investigation is performed for the MHD viscous nanofluid due to convective stretching. Heat and mass transfer are investigated for steady, viscous dissipations and chemical reactions. Matta, S., Malga, B.S et al **[39]** To study the effects of Viscous Dissipation on MHD free convection flow past a semi-infinite moving vertical porous plate with heat sink and chemical reaction. The governing dimensionless coupled equations are solved by using Finite Element Method. Kumar, P. P., Malga, B. S et al **[40]** the impact of Dufour number along with viscous dissipation on the non-steady stream of heat together with the mass transfer of Casson fluid, on vertical permeable laminate is studied with chemical reaction. Dimensionless governing equations of temperature, velocity as well as concentration have been resolved by the finite element method (FEM).

3. Methodology

When investigating heat transfer enhancement by the addition of different nanofluids (CuO, Al_2O_3, ZnO) in a vertical rotating system, your methodology should comprehensively address the experimental or numerical setup, nanofluid preparation, system configuration, parameters measured, and the analysis approach.

Numerical Works

The cylinders' geometry when L/DH= 60. The Reynolds number is determined by assigning a uniform velocity at the entrance. Assuming all derivatives are zero, it is believed that the flow is fully developed at the outlet. The inner shaft is heated by a steady stream of heat while the outer tube and walls of the inner shaft rotate in a non-slip state. Gravity was disregarded in this simulation because it took place in a chaotic environment.

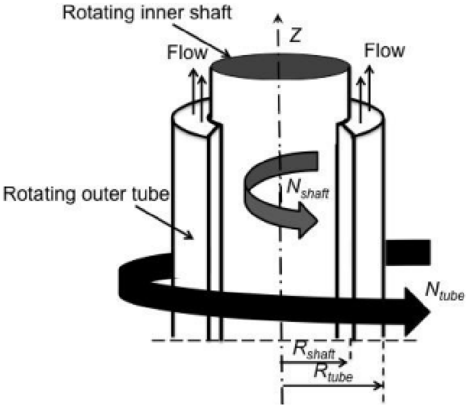

Fig 1: Geometry of the study

Fluid properties

The investigate the thermal and physical characteristics of nanofluids containing copper (Cu), aluminum oxide (Al_2O_3), and zinc oxide (ZnO) nanoparticles at a concentration of 2% by volume in comparison to water as the base fluid. These are usually measured at room temperature (~25°C) and find widespread use in heat transfer applications.

Table 1: Nanofluids with 2% Volume Concentration

Property	CuO	Al_2O_3	ZnO
Density (kg/m³)	~1025–1035	~1015–1025	1010–1020
Specific Heat Capacity (J/kg·K)	3850	~4000	4100
Thermal Conductivity (W/m·K)	0.75–0.85	~0.68–0.75	0.65–0.73
Dynamic Viscosity (Pa·s)	1.1×10^{-3}	1.05×10^{-3}	1.02×10^{-3}

Governing Equations

To simplify the numerical study, we have assumed steady and incompressible flow conditions. Since the current study's mass flow rates are indicative of turbulent flow conditions, the two-equation "k-ε" turbulence model was employed for turbulence modeling. The "k-ε" turbulence model has been utilized because it is adaptable and strong enough to deal with various types of turbulent flows. There are less convergence issues and the model is stable. The equations that govern the flow are given below.

Turbulence Modeling: To account for the turbulent changes in velocity and temperature, use a suitable turbulence model (such as k−ϵ, k−ϋ, or Reynolds Stress Model) if the flow regime is predicted to be turbulent (according to Reynolds number). It is important to consider the flow properties and available computational resources while choosing a turbulence model.

Conservation of mass:

$$\nabla.(\rho\vec{V}) = 0. \quad \text{……………………} \quad (1)$$

Momentum equation:

X-momentum:

$$\nabla.(\rho u\vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}. \quad \text{……………………………….} \quad (2)$$

Y-momentum:

$$\nabla.(\rho v\vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho g. \quad \text{………………………………….} \quad (3)$$

Z-momentum:

$$\nabla.(\rho w\vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \quad \text{………………………………….} \quad (4)$$

Energy equation:

$$\nabla.(\rho e\vec{V}) = -p\nabla.\vec{V} + \nabla.(k\nabla T) + q + \varnothing, \quad \text{……………………………………} \quad \mathbf{(5)}$$

4.RESULT AND DISCUSSION

To calculated the non-dimensional velocities, temperatures, species concentrations, skin-friction, and Nusselt numbers using three different kinds of water-based nanofluids and particular values for the parameters that go into the equation to better understand the problem from a physical standpoint.

for S=1.0; ε =0.02; R=0.02 n=10.0; t=0.1; M=0.5, F=1.0; Q=10.0 φ =0.15; K=0.05.

Table 2: Values of φ and skin friction (M) for various conditions.

M	ϕ	**Skin Friction** ε =0.01;n=10.0; $t = \pi/2$ F=1.0;Pr=6.2; Q=10.0; K=0.05; R=0.02, S=1.0		
		CuO	*ZnO*	Al_2O_3
0.0	0.1	0.602330	0.466185	0.382986
	0.2	0.395930	0.315610	0.270562
	0.3	0.175042	0.158834	0.135920
	0.4	0.028650	0.025187	0.024582
0.5	0.1	0.602547	0.473703	0.383277
	0.2	0.396003	0.319424	0.270715
	0.3	0.175100	0.162048	0.135992
	0.4	0.028734	0.025256	0.024630
1.0	0.1	0.602758	0.481499	0.383573
	0.2	0.396079	0.323406	0.270871
	0.3	0.175162	0.166150	0.136063
	0.4	0.028820	0.025313	0.024682

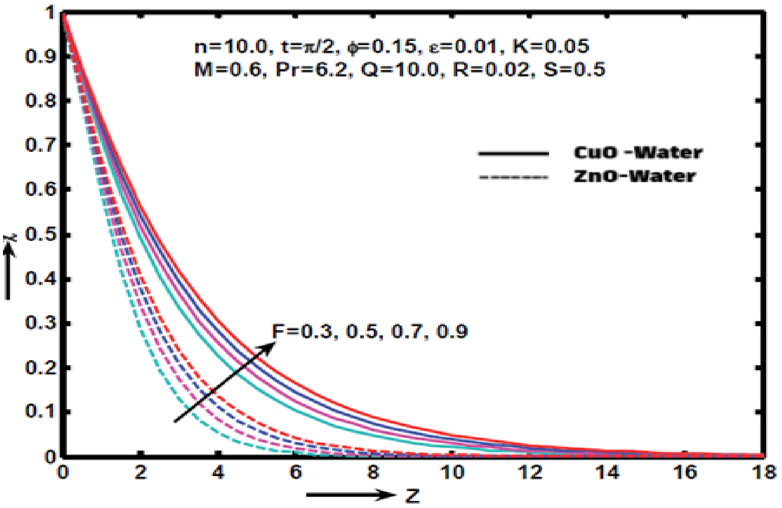

Fig 2: Velocity profile for various values of F

The plot illustrates the velocity profile (χ vs z) for different values of the parameter F = 0.3, 0.5, 0.7, 0.9, comparing two nanofluids: CuO–Water (solid lines) and ZnO–Water (dashed lines) under the same physical conditions. CuO–Water (solid lines) consistently shows higher velocity than ZnO–Water (dashed lines) for the same F, suggesting that CuO–Water has superior momentum transport characteristics in this setup

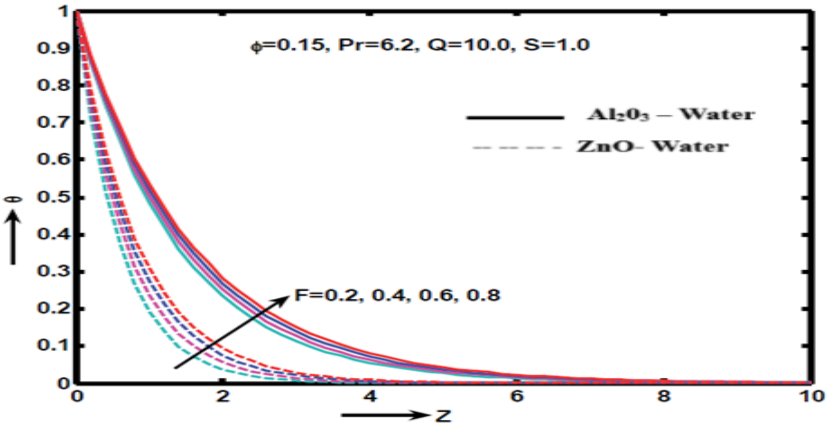

Fig 3: Temperature profile for various values of F

The reason it appears in figure 3 is because the thermal boundary layer gets thicker as the temperature rises. It follows that less radiation is required for the cooling process to proceed with greater velocity. Nanofluid velocities and temperatures are found to be lower in ZnO-water nanofluids compared to Zno-water and Al2O3-water combinations. This event is more in line with what we know from the physical world.

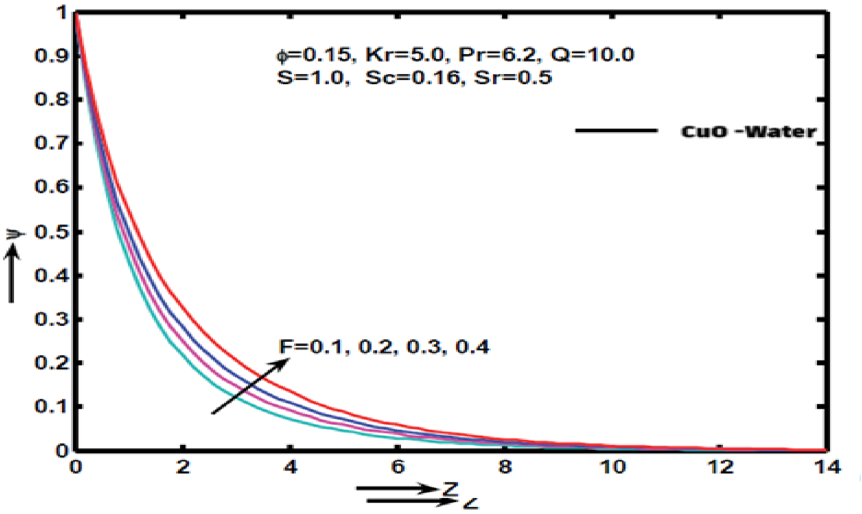

Fig 4: Concentration profile for various values of F

Figure 4 shows shows the concentration profile ψ versus z for CuO–Water nanofluid at various values of the parameter F = 0.1, 0.2, 0.3, 0.4 under specified physical conditions. The parameter F appears to enhance mass transfer; higher F leads to stronger diffusion effects or perhaps higher mass flux from the boundary

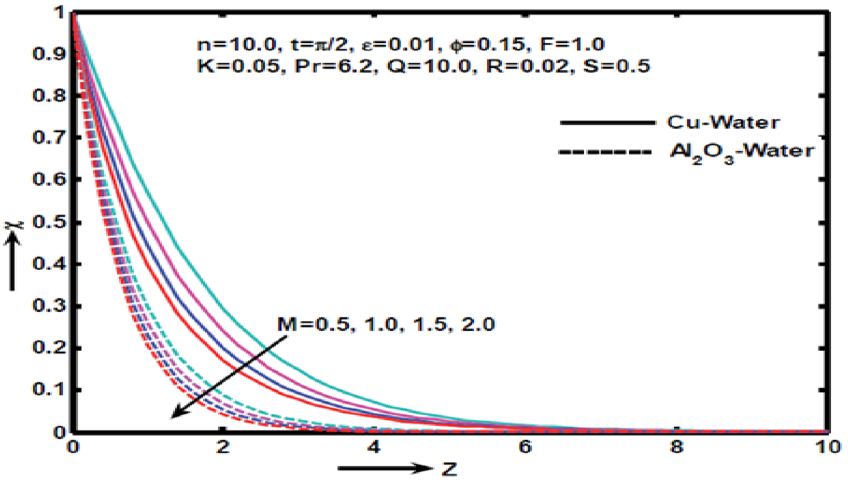

Fig. 5: Velocity profile for various values of M

Shows fig 5 the velocity profile χ versus z for Cu–Water (solid lines) and Al_2O_3–Water (dashed lines) nanofluids under varying values of the magnetic parameter $M = 0.5, 1.0, 1.5, 2.0$ Cu–Water nanofluid offers less resistance to magnetic suppression, hence shows higher velocity profiles compared to Al_2O_3–Water, likely due to differences in thermal conductivity and viscosity.

Conclusion:

The research verifies that when compared to the base fluid, the three nanofluids (CuO, Al_2O_3, and ZnO) improve heat transmission. The enhanced thermal conductivity, Brownian motion, and enhanced energy transfer capacities of the dispersed nanoparticles in the fluid are responsible for this improvement. The CuO nanofluid exhibited the highest heat transfer performance across all operating conditions, due to its superior thermal conductivity which enhances convective and conductive heat transfer. Increasing nanoparticle volume fraction improves heat transfer but also increases viscosity, which may lead to higher pumping power requirements and potential flow resistance. CuO showed the best trade-off between enhancement and viscosity rise at moderate concentrations (~0.5%–1%). For systems prioritizing maximum heat transfer efficiency (e.g., cooling of rotating machinery, rotating heat exchangers), CuO nanofluid is recommended.

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