

Special Issue on Symmetry and Fluid Mechanics

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Abstract: This Special Issue invited researchers to contribute their original research work and review articles on “Symmetry and Fluid Mechanics” that either advances the state-of-the-art mathematical methods through theoretical or experimental studies or extends the bounds of existing methodologies with new contributions related to the symmetry, asymmetry, and lie symmetries of differential equations proposed as mathematical models in fluid mechanics, thereby addressing current challenges. In response to the call for papers, a total of 42 papers were submitted for possible publication. After comprehensive peer review, only 25 papers qualified for acceptance for final publication. The rest of the papers could not be accommodated. The submissions may have been technically correct but were not considered appropriate for the scope of this Special Issue. The authors are from geographically distributed countries such as the USA, Australia, China, Saudi Arabia, Iran, Pakistan, Malaysia, Abu Dhabi, UAE, South Africa, and Vietnam. This reflects the great impact of the proposed topic and the effective organization of the guest editorial team of this Special Issue.

Keywords: Newtonian and non-Newtonian fluids; nanofluids and particle shape effects; convective heat and mass transfer; steady and unsteady flow problems; multiphase flow simulations; fractional order differential equations; thermodynamics; physiological fluid phenomena in biological systems

1. Introduction

In fluid mechanics, the equations that govern the flows are usually very complex, involve a number of parameters, are inherited nonlinear in nature, and cannot be solved by traditional methods. Due to the complexity of these equations, finding analytical or semi-analytical or even numerical solutions is very important for many reasons, for instance, they provide a standard for checking the imperial results. Therefore, several new techniques have been developed. We hope that this issue will not only serve the said purpose but will also provide an overall picture and up-to-date findings to readers of the scientific community that ultimately benefits the industrial sector regarding its specific market niches and end users.

2. Methodologies and Usages

The Lagrangian meshfree particle-based method has advantages in solving fluid dynamics problems with complex or time-evolving boundaries for a single phase or multiple phases. A pure Lagrangian meshfree particle method based on a generalized finite difference (GFD) scheme is proposed by Zhang and Xiongin [1] to simulate time-dependent weakly compressible viscous flow. The flow is described with Lagrangian particles, and the partial differential terms in the Navier–Stokes equations are represented as the solution to a symmetric system of linear equations through a GFD scheme. In solving the particle-based symmetric equations, the numerical method only needs the kernel function

itself instead of using its gradient, i.e., the approach is a kernel gradient free (KGF) method, which avoids the use of artificial parameters to solve the viscous term and reduces the limitations of using the kernel function. Moreover, the order of Taylor series expansion can easily be improved in the meshless algorithm. In this paper, the particle method is validated with several test cases, and the convergence, accuracy, and different kernel functions are evaluated.

In [2], an analytical study on blood flow analysis with a tapered porous channel is presented. The blood flow was driven by peristaltic pumping. Thermal radiation effects were also taken into account. The convective and slip boundary conditions were also applied in this formulation. These conditions are very helpful for carrying out the behavior of particle movement which may be utilized for cardiac surgery. The tapered porous channel had an unvarying wave speed with dissimilar amplitudes and phase. The non-dimensional analysis was utilized for some approximations, for example, the proposed mathematical modelling equations were modified by using a lubrication approach and the analytical solutions for stream function, nanoparticle temperature, and volumetric concentration profiles were obtained. The impacts of various emerging parameters on the thermal characteristics and nanoparticle concentration were analyzed with the help of computational results. The trapping phenomenon was also examined for relevant parameters. It was also observed that the geometric parameters, like amplitudes, non-uniform parameters, and phase difference, play important roles in controlling the nanofluid transport phenomena. The outcomes of the present model may be applicable for the smart nanofluid peristaltic pump which may be utilized in hemodialysis.

As magnetohydrodynamics (MHD) deals with the analysis of electrically conducting fluids and the study of nanofluids, considering the influence of MHD phenomena is a topic of great interest from industrial and technological points of view. Thus, the modified MHD mixed convective, nonlinear, radiative, and dissipative problem was modelled over an arc-shaped geometry for $\text{Al}_2\text{O}_3 + \text{H}_2\text{O}$ nanofluid at 310 K with a freezing temperature of 273.15 K by Khan et al. [3]. Firstly, the model was reduced into a coupled set of ordinary differential equations using similarity transformations. The impact of the freezing temperature and the molecular diameter were incorporated in the energy equation. Then, the Runge–Kutta scheme, along with the shooting technique, was adopted for the mathematical computations, and code was written in Mathematica 10.0. Further, a comprehensive discussion of the flow characteristics is provided. The results for the dynamic viscosity, heat capacity, and effective density of the nanoparticles were examined for various nanoparticle diameters and volume fractions

Jalali et al. [4] reported on laminar heat transfer and direct fluid jet injection of oil/MWCNT nanofluid using a numerical investigation with a finite volume method. Both slip and no-slip boundary conditions on solid walls were used. The objective of this study was to increase the cooling performance of heated walls inside a rectangular microchannel. The Reynolds numbers ranged from 10 to 50; slip coefficients were 0.0, 0.04, and 0.08; and nanoparticle volume fractions were 0%–4%. The results showed that using techniques for improving heat transfer, such as fluid jet injection with low temperature and adding nanoparticles to the base fluid, allowed for good results to be obtained. By increasing jet injection, areas with eliminated boundary layers along the fluid direction spread in the domain. Dispersing solid nanoparticles in the base fluid with higher volume fractions resulted in a better temperature distribution and Nusselt number. By increasing the nanoparticle volume fraction, the temperature of the heated surface penetrated the flow centerline, and the fluid temperature increased. Jet injection with higher velocity, due to its higher fluid momentum, resulted in a higher Nusselt number and affected lateral areas. The fluid velocity was higher in jet areas, which diminished the effect of the boundary layer.

The non-Newtonian fluid model named Casson fluid was considered by Rehman et al. [5]. The semi-infinite domain of the disk was fitted out with magnetized Casson liquid. The roles of both thermophoresis and Brownian motion were inspected by considering nanosized particles in a Casson liquid spaced above the rotating disk. The magnetized flow field was framed with Navier's slip assumption. The Von Karman scheme was adopted to transform flow narrating equations in terms

of a reduced system. For better depiction, a self-coded computational algorithm was executed rather than the move-on with build-in array. Numerical observations via magnetic elements, Lewis numbers, Casson, slip, Brownian motion, and thermophoresis parameters subject to radial and tangential velocities, temperature, and nanoparticle concentration are reported. The validation of the numerical method being used is given through a comparison with existing work. Comparative values of the local Nusselt number and local Sherwood number are provided for the involved flow controlling parameters.

Alshomrani and Ullah [6] inspected velocity slip impacts in the three-dimensional flow of water-based carbon nanotubes because of a stretchable rotating disk. Nanoparticles like single and multi-walled carbon nanotubes (CNTs) were utilized. Graphical outcomes were acquired for both single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). The heat transport system was examined in the presence of thermal convective condition. Proper variables led to a strong nonlinear standard differential framework. The associated nonlinear framework was tackled by an optimal homotopic strategy. Diagrams were plotted so as to examine how the temperature and velocities are influenced by different physical variables. The coefficients of skin friction and the Nusselt number are exhibited graphically. Our results indicate that the skin friction coefficient and Nusselt number are enhanced for larger values of nanoparticle volume fraction.

The Darcy–Brinkman flow over a stretching sheet in the presence of frictional heating and porous dissipation was examined in [7]. The governing equations were modeled and simplified under boundary layer approximations, which were then transformed into a system of self-similar equations using appropriate transformations. The resulting system of nonlinear equations was solved numerically under velocity and thermal slip conditions by the fourth-order Runge–Kutta method and built-in routine `bvp4c` in Matlab. Under special conditions, the obtained results were compared with the results available in the literature. An excellent agreement was observed. The variation of parameters was studied for different flow quantities of interest, and the results are presented in the form of tables and graphs.

The Couette–Poiseuille flow of couple stress fluid with a magnetic field between two parallel plates was investigated by Ellahi et al. [8]. The flow was driven due to the axial pressure gradient and uniform motion of the upper plate. The influence of heating at the wall in the presence of spherical and homogeneous Hafnium particles was taken into account. The temperature dependent viscosity model, namely, Reynolds' model was utilized. The Runge–Kutta scheme with shooting was used to tackle a non-linear system of equations. It was observed that the velocity decreased by increasing the values of the Hartman number, as heating of the wall reduced the effects of viscous forces; therefore, the resistance of magnetic force reduced the fluid velocity. However, due to shear thinning effects, the velocity was increased by increasing the values of the viscosity parameter, and as a result, the temperature profile also declined. The suspension of inertial particles in an incompressible turbulent flow with Newtonian and non-Newtonian base fluids can be used to analyze the biphasic flows through diverse geometries that could possibly be future perspectives of the proposed model.

Characteristically, most fluids are not linear in their natural forms and therefore, fractional order models are very appropriate for handling these kinds of phenomena. In [9], the authors studied the base solvents of water and ethylene glycol for the stable dispersion of graphene oxide to prepare graphene oxide–water (GO-W) and graphene oxide–ethylene glycol (GO-EG) nanofluids. The stable dispersion of the graphene oxide in the water and ethylene glycol was taken from the experimental results. The combined efforts of the classical and fractional order models were imposed and compared under the effect of the Marangoni convection. The numerical method for the non-integer derivative that was used in this research is known as a predictor corrector technique of the Adams–Bashforth–Moulton method (Fractional Differential Equation-12 or shortly, FDE-12). The impacts of the modeled parameters were analyzed and compared for both GO-W and GO-EG nanofluids. The diverse effects of the parameters were observed through a fractional model rather than using the traditional approach. Furthermore, it was observed that GO-EG nanofluids are more efficient due to their high thermal properties compared with GO-W nanofluids.

In [10], instead of the more customary parabolic Fourier law, the hyperbolic Cattaneo–Christov (C–C) heat flux model was used to jump over the major hurdle of “parabolic energy equation”. The more realistic three-dimensional Carreau fluid flow analysis was conducted with the attendance of temperature-dependent thermal conductivity. The other salient impacts affecting the considered model are the homogeneous-heterogeneous (h-h) reactions and magnetohydrodynamics (MHD). The boundary conditions supporting the problem are convective heat and h-h reactions. The considered boundary layer problem was addressed via similarity transformations to obtain the system of coupled differential equations. The numerical solutions were attained by undertaking the MATLAB built-in function `bvp4c`. To comprehend the consequences of assorted parameters on involved distributions, different graphs were plotted and are accompanied by requisite discussions in light of their physical significance. To substantiate the presented results, a comparison with the already conducted problem is also given. It is envisaged that there is a close correlation between the two results. This shows that dependable results are being submitted. It is noticed that h-h reactions depict an opposite behavior compared with the concentration profile. Moreover, the temperature of the fluid augments the values of thermal conductivity parameters.

The aim of [11] was to present an analysis of local similarity solutions of Casson fluid over a non-isothermal cylinder subject to suction/blowing. The cylinder was placed inside a porous medium and stretched in a nonlinear way. Further, the impacts of chemical reactions, viscous dissipation, and heat generation/absorption on flow fields were also investigated. Similarity transformations were employed to convert the nonlinear governing equations to nonlinear ordinary differential equations and then solved via the Keller box method. The findings demonstrate that the magnitude of the friction factor and mass transfer rate are suppressed with an increment in the Casson parameter, whereas the heat transfer rate was found to be intensified. An increase in the curvature parameter enhanced the flow field distributions. The magnitude of wall shear stress was found to be higher with an increase in the porosity and suction/blowing parameters.

The pressure-driven flow in the slip regime was investigated in rectangular microducts by Ullah et al. [12]. In this regime, the Knudsen number lay between 0.001 and 0.1. The duct aspect ratio was taken as $0 \leq \varepsilon \leq 1$. Rarefaction effects were introduced through the boundary conditions. The dimensionless governing equations were solved numerically using MAPLE, and MATLAB was used for artificial neural network modeling. Using a MAPLE numerical solution, the shear stress and heat transfer rate were obtained. The numerical solution could be validated for special cases when there was no slip (continuum flow), $\varepsilon = 0$ (parallel plates), and $\varepsilon = 1$ (square microducts). An artificial neural network was used to develop separate models for the shear stress and heat transfer rate. Both physical quantities were optimized using a particle swarm optimization algorithm. Using these results, the optimum values of both physical quantities were obtained in the slip regime. It is shown that the optimal values ensue for the square microducts at the beginning of the slip regime.

Unidirectional flows of fractional viscous fluids in a rectangular channel were studied in [13]. The flow was generated by the shear stress given on the bottom plate of the channel. The authors developed a generalized model on the basis of constitutive equations described by the time-fractional Caputo–Fabrizio derivative. Many authors have published different results by applying the time-fractional derivative to the local part of acceleration in the momentum equation. This fractional model approach does not have a sufficient physical background. By using fractional generalized constitutive equations, they developed a proper model to investigate exact analytical solutions corresponding to the channel flow of a generalized viscous fluid. The exact solutions for the velocity field and shear stress were obtained by using Laplace transform and Fourier integral transformation for three different cases, namely, (i) constant shear, (ii) ramped type shear, and (iii) oscillating shear. The results are plotted and discussed.

The research article in [14] deals with the determination of magnetohydrodynamic steady flow of three combined nanofluids (Jeffery, Maxwell and Oldroyd-B) over a stretched surface. The surface was considered to be linear. The Cattaneo–Christov heat flux model was considered necessary to study the

relaxation properties of the fluid flow. The influence of homogeneous-heterogeneous reactions (active for auto catalysts and reactants) were taken into account. The modeled problem was solved analytically. The impressions of the magnetic field, Prandtl number, thermal relaxation time, Schmidt number, and homogeneous-heterogeneous reaction strength were considered through graphs. The velocity field diminished with an increasing magnetic field. The temperature field diminished with an increasing Prandtl number and thermal relaxation time. The concentration field upsurged with an increasing Schmidt number, which decreased with an increasing homogeneous-heterogeneous reaction strength. Furthermore, the impacts of these parameters on skin fraction, Nusselt number, and Sherwood number are also accessible through tables. A comparison between analytical and numerical methods is presented both graphically and numerically.

In the study presented in [15], Jeffrey fluid was studied in a microgravity environment. Unsteady two-dimensional incompressible and laminar g-Jitter mixed convective boundary layer flow over an inclined stretching sheet was examined. Heat generation and magnetohydrodynamic (MHD) effects were also considered. The governing boundary layer equations together with boundary conditions were converted into a non-similar arrangement using appropriate similarity conversions. The transformed system of equations was resolved mathematically by employing an implicit finite difference pattern through a quasi-linearization method. Numerical results of temperature, velocity, local heat transfer and local skin friction coefficient were computed and plotted graphically. It was found that local skin friction and local heat transfer coefficients increased for an increasing Deborah number when the magnitude of the gravity modulation was unity. Assessment with previously published results showed an excellent agreement.

The two-dimensional laminar incompressible magnetohydrodynamic steady flow over an exponentially shrinking sheet with the effects of slip conditions and viscous dissipation was examined by Lund et al. [16]. An extended Darcy Forchheimer model was considered to observe the porous medium embedded in a non-Newtonian Casson-type nanofluid. The governing equations were converted into nonlinear ordinary differential equations using an exponential similarity transformation. The resultant equations for the boundary values problem (BVPs) were reduced to initial value problems (IVPs) and then the shooting and fourth-order Runge–Kutta methods (RK-4th method) were applied to obtain numerical solutions. The results reveal that multiple solutions occur only for the high suction case. The results of the stability analysis showed that the first (second) solution is physically reliable (unreliable) and stable (unstable).

A mathematical model of a convection flow of magnetohydrodynamic (MHD) nanofluid in a channel embedded in a porous medium is introduced by Khan and Alqahtni [17]. The flow along the walls, characterized by a non-uniform temperature, is under the effect of the uniform magnetic field acting transversely to the flow direction. The walls of the channel are permeable. The flow is due to convection combined with uniform suction/injection at the boundary. The model was formulated in terms of unsteady, one-dimensional partial differential equations (PDEs) with imposed physical conditions. The cluster effect of nanoparticles was demonstrated in the $C_2H_6O_2$, and H_2O base fluids. The perturbation technique was used to obtain a closed-form solution for the velocity and temperature distributions. Based on numerical experiments, it was concluded that both the velocity and temperature profiles are significantly affected by ϕ . Moreover, the magnetic parameter retards the nanofluid motion whereas porosity accelerates it. Each H_2O -based and $C_2H_6O_2$ -based nanofluid in the suction case had a higher magnitude of velocity as compared to the injections case.

An analytical simulation of the head-on collision between a pair of hydroelastic solitary waves propagating in opposite directions in the presence of a uniform current was proposed by Bhatti and Qiang [18] for an infinite, thin, elastic plate floating on the surface of water. The mathematical modeling of the thin elastic plate was based on the Euler–Bernoulli beam model. The resulting kinematic and dynamic boundary conditions were highly nonlinear and were solved analytically with the help of a singular perturbation method. The Poincaré–Lighthill–Kuo method was applied to obtain the solution of the nonlinear partial differential equations. The resulting solutions are presented separately for the

left- and right-going waves. The behaviors of all emerging parameters are presented mathematically and discussed graphically for the phase shift, maximum run-up amplitude, distortion profile, wave speed, and solitary wave profile. It was found that the presence of a current strongly affects the wavelength and wave speed of both solitary waves. A graphical comparison with pure-gravity waves is also presented as a particular case study.

The 3D magnetohydrodynamic (MHD) rotational nanofluid flow through a stretching surface was investigated in the study presented in [19]. Carbon nanotubes (SWCNTs and MWCNTs) were used as nano-sized constituents, and water was used as a base fluid. The Cattaneo–Christov heat flux model was used for the heat transport phenomenon. This arrangement had remarkable visual and electronic properties, such as strong elasticity, high updraft stability, and natural durability. The heat interchanging phenomenon was affected by updraft emission. The effects of nanoparticles such as Brownian motion and thermophoresis were also included in the study. By considering the conservation of mass, motion quantity, heat transfer, and nanoparticle concentration, the whole phenomenon was modeled. The modeled equations were highly non-linear and were solved using the homotopy analysis method (HAM). The effects of different parameters are described in the tables, and their impacts on different state variables are displayed in graphs. Physical quantities like the Sherwood number, Nusselt number, and skin friction are presented through tables with the variations of different physical parameters.

The fractional order model is the most suitable model for representing such phenomena compared with other traditional approaches. The forced convection fractional order boundary layer flow comprising single-wall carbon nanotubes (SWCNTs) and multiple-wall carbon nanotubes (MWCNTs) with variable wall temperatures passing over a needle was examined in [20]. The numerical solutions for the similarity equations were obtained for the integer and fractional values by applying the Adams-type predictor corrector method. A comparison of the SWCNTs and MWCNTs for the classical and fractional schemes was investigated. The classical and fractional order impacts of the physical parameters such as skin fraction and Nusselt number are presented physically and numerically. It was observed that the impacts of the physical parameters over the momentum and thermal boundary layers in the classical model were limited; however, while utilizing the fractional model, the impacts of the parameters varied at different intervals.

A steady laminar flow over a vertical stretching sheet with the existence of viscous dissipation, heat source/sink, and magnetic fields was numerically inspected in [21] through a shooting scheme based Runge–Kutta–Fehlberg-integration algorithm. The governing equation and boundary layer balance were expressed and then converted into a nonlinear normal system of differential equations using suitable transformations. The impacts of the physical parameters on the dimensionless velocity, temperature, the local Nusselt, and skin friction coefficient are described. The results show good agreement with recent research. The findings reveal that the Nusselt number at the sheet surface augments, since the Hartmann number, stretching velocity ratio A , and Hartmann number Ha increase. Nevertheless, it reduces with respect to the heat generation/absorption coefficient δ .

The impacts of Newtonian heating and homogeneous-heterogeneous (h-h) reactions on the flow of Ag–H₂O nanofluid over a cylinder which is stretched in a nonlinear way are discussed in [22]. The additional effects of magnetohydrodynamics (MHD) and nonlinear thermal radiation are also added features of the problem under consideration. The shooting technique is used to obtain the numerical solution to the problem which comprises highly nonlinear system ordinary differential equations. The sketches of different parameters versus the involved distributions are given with requisite deliberations. The obtained numerical results are matched with those of an earlier published work, and an excellent agreement exists between them. From our obtained results, it is concluded that the temperature profile is enriched with augmented values of radiation and curvature parameters. Additionally, the concentration field is a declining function of the strength of h-h reactions.

The research conducted in [23] gives a remedy for the malignant tissues, cells, or clogged arteries of the heart by means of permeating a slim tube (i.e., catheter) in the body. The tiny size gold particles

drift in the free space of catheters with flexible walls with coupled stress fluid. To improve the efficiency of curing and to speed up the process, activation energy was added to the process. The modified Arrhenius function and Buongiorno model, respectively, moderated the inclusion of activation energy and nanoparticles of gold. The effects of the chemical reaction and activation energy on peristaltic transport of nanofluids were also taken into account. It was found that the golden particles encapsulate large molecules to transport essential drugs efficiently to the affected part of the organ.

The aim of [24] was to study time-dependent, rotating, single-wall, electrically conducting carbon nanotubes with aqueous suspensions under the influence of nonlinear thermal radiation in a permeable medium. The impact of viscous dissipation was taken into account. The basic governing equations, in the form of partial differential equations (PDEs), were transformed into a set of ordinary differential equations (ODEs) suitable for transformations. The homotopy analysis method (HAM) was applied to obtain the solution. The effects of numerous parameters on the temperature and velocity fields are explained by graphs. Furthermore, the action of significant parameters on the mass transportation and the rates of friction factor were determined and discussed by plots in detail. The boundary layer thickness was reduced by a greater rotation rate parameter in our established simulations. Moreover, velocity and temperature profiles decreased with increases in the unsteadiness parameter. The action of the radiation phenomena acts as a source of energy to the fluid system. For a greater rotation parameter value, the thickness of the thermal boundary layer decreases. The unsteadiness parameter rises with velocity and the temperature profile decreases. A higher value of ϕ augments the frictional force strength within a liquid motion. For greater R and θw , the heat transfer rate rises. The temperature profile reduces with rising values of Pr .

An axisymmetric three-dimensional stagnation point flow of a nanofluid on a moving plate with different slip constants in two orthogonal directions in the presence of a uniform magnetic field was considered by Sadiq [25]. The magnetic field was considered along the axis of the stagnation point flow. The governing Navier–Stokes equation, along with the equations of nanofluid for three-dimensional flow, was modified using similarity transform, and reduced nonlinear coupled ordinary differential equations were solved numerically. It was observed that the magnetic field M and slip parameter λ_1 increased the velocity and decreased the boundary layer thickness near the stagnation point. Also, a thermal boundary layer was achieved earlier than the momentum boundary layer with increases in the thermophoresis parameter Nt and Brownian motion parameter Nb . Important physical quantities, such as skin friction and the Nusselt and Sherwood numbers, were also computed and are discussed through graphs and tables.

3. Future Trends in Fluid Mechanics

Even with the completion of this Special Issue, the material that advances the state-of-the-art experimental, numerical, and theoretical methodologies or extends the bounds of existing methodologies through new contributions in fluid mechanics is still insufficient. Nanofluid technology can also help with the development of better industrial applications in fluid mechanics. As in the fields of fluid dynamics and mechanical engineering, most nanofluids are generally not linear in character; therefore, techniques like symmetry methods can help us to find meaningful solutions to nonlinear resulting equations.

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