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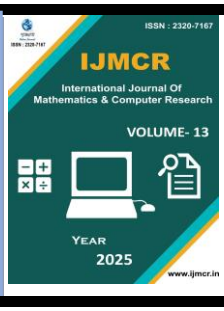

A Comprehensive Review on the Dynamics of Fine Dust in Three-Dimensional Fluctuating Couette Flow of Heat and Mass Transfer

K. Sharmilaa[1], A. Rohith Roshsan[2]

[1]Department of Mathematics, PSGR Krishnammal College for Women, Coimbatore. 641004.

[2]Department of Mechanical Engineering, Engineering Design Division College of Engineering, Guindy, Chennai.600025.

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Corresponding Author:
K. Sharmilaa

ABSTRACT

Studies of dust laden Couette flow have evolved from fundamental equilibrium calculations to advanced multiphase heat and mass transfer theory. Recent investigations explore the effects of rotation, magneto hydrodynamic fields, slip, suction/injection, and resistance in porous media. Results show that the medium constraints and edge forces have a significant impact on flow and thermal properties, highlighting their importance in enhancing the performance of Couette flows.

KEYWORDS: Couette flow, porous medium, dusty fluid, Heat transfer, mass transfer

I. INTRODUCTION

Couette flow is a fundamental concept in fluid mechanics which describes the laminar stream of a viscous fluid among two parallel surfaces, in which one surface is fixed and the other moves with a continuous velocity. Dusty fluids are used to reduce the temperature of the system as fine dust particles are embedded in air or liquid, which serves as a working medium.

II. ANALYTICAL STUDIES

Gerstein and Gross (1974) examined the movement and heat transmission beside a smooth wall with periodic pressure. Their research illustrated how periodically varied suction in a wall alters the boundary-layer structure and thereby impacts velocity distribution as well as heat transfer behaviour, emphasising the critical role of periodic suction in regulating wall shear stress and thermal conduction in boundary-layer flows.

Singh, Sharma and Mishra (1977) investigated the three dimensional movement brought through time dependent transverse sinusoidal suction velocity over a porous plate. The application of sinusoidal suction was found to change the current structure after the usual two dimensional case towards a three dimensional one. The solution was obtained for providing the wall shear stress and the heat transmission rate. It was noted that in the asymptotic limit of vanishing frequency constraint, the cross-flow skin friction precedes the phase by $\pi/2$, highlighting the involvement of oscillatory suction in altering together the momentum and current boundary layers.

Singh et al (1978) analysed theoretically of fluid flow along a porous plate placed normal to the flow, where the system is exposed to a crosswise sinusoidal velocity profile. This forcing gives rise to a three-dimensional nature in the flow field. For the asymptotic limit case, the wall shear stress in the direction of primary flow is calculated for numerous standards of the buoyancy parameter G.

Prasad and Ramacharyulu (1979) studied flow of a viscous fluid with uniformly distributed dust particles among two parallel plates under the effect of an imprudent density ramp. Systematic terms were derived for fluid and dust particle velocities. The investigation also explored total flux variations of the two phases and noted the effect of dust loading on skin friction.

Singh (1980) analysed the three dimensional viscous movement above a porous plate to influence the heat transmission. The speed components in all the spatial directions were considered and the influence of viscosity was emphasized in defining the flow behaviour. The porous character of the plate allowed for fluid intrusion, which introduced complexity to the flow field. The research identifies the coupled momentum and thermal energy transport effects and the results provided the significant information for cooling systems, filtration operations, and fluid injection or removal through permeable boundaries.

Dixit (1980) investigated unstable flow of dusty viscous fluid in four sided ducts. The study considered the

behaviour of flow under time-dependent pressure gradients affected by the occurrence of dust particles. Based on the two phase nature of the flow, the study emphasized the contact between the dust particles and the fluid and their contribution to velocity distribution in the duct. This research also examined the influence of duct geometry on flow properties and presented understanding of momentum exchange and stability of flows in dusty fluid systems. This work adds to the knowledge of particulate-laden flows in ducts and channels where unsteadiness prevails.

Lokenath Debnath and Ghosh (1988) studied the initial value problem of an incompressible viscous fluid having small dust particles, confined between two endless non directing plates. The flow was caused by rectilinear oscillations of the plates with prescribed frequencies in an external transverse magnetic field. Particular solutions for fluid velocity, particle velocity, wall shear stress were obtained by the operational method. This research demonstrated that the result of dust particles on fluid velocity is a function of the fluctuation period for high frequencies, which slows down the motion. While for lower frequencies, it first increases fluid velocity up to the point of equilibrium, then its action is to oppose the flow.

Daskalakis (1990) obtained velocity and temperature distribution for impulsive Couette flow of a high, temperature reliant on viscosity fluid over a porous medium. Both transient and steady states were examined, with specific focus on the effect of medium porousness. The findings indicate, in the stable state, low porousness results in a higher maximum temperature but with greatly reduces velocity profiles. During the transient state, velocity development was found to be considerably quicker than temperature, a trend augmented by the porous medium. Further, it was found that the permeability causes skewed temperature profiles and increased temporal temperature gradients throughout the process.

Kuznetsov (1998) studied fluid dynamics and thermal exchange in Couette flow over a fluid soaked porous medium. The flow was caused by a wall in motion due to a plane and was characterised by extended Darcy equation of Brinkman–Forchheimer. Heat transfer was studied in two cases: heat flux at wall with an insulated moving wall, and an insulated wall with a heat flux moving wall. Analytical expressions were obtained for velocity profile, temperature field, and Nusselt number. The investigation was also extended to Couette flow and observed how porous layer distribution and presence affect both flow and thermal properties.

Singh (1999) investigated Couette flow among two parallel flat porous plates with crosswise sinusoidal inoculation in the plate and parallel continuous suction through the uniformly moving plate. This type of injection created a three-dimensional flow field. Applying series extension approach, the author derived logical results for the velocity and temperature circulations. The study revealed that the heat transmission coefficient diminishes as the injection constraint rises, indicating the role of transverse mass transfer in both momentum and heat transfer in Couette systems.

Kuznetsov (2000) investigated completely settled Couette movement in a compound station, which is filled by a pure liquid and by a porous medium soaked with fluid. The movement was caused by the effort of the plate surrounding to clear liquid zone, the porous zone was surrounded by an immovable plate. Considering the flow between an adiabatic plate and an immovable plate under a uniform heat flux, the velocity and temperature field boundary layer solutions were found.

Singh and Sharma (2001) examined steady laminar three dimensional Couette flow of a viscous fluid among two infinite flat porous plates imbedded in a porous medium. The flow arrangement was in a manner that the continuous pressure at the upper plate and crosswise sinusoidal inoculation at the lowest plate. Their work related the effects of porous media resistance and transverse mass transfer and shed light on momentum transport under mixed suction–injection conditions.

Singh (2004) considered the effect of a translating magnetic field on three dimensional Couette flow between two porous plates. In the setup, the porous plate was exposed to periodic force, whereas the top porous plate was subjected to uniform suction. The author derived an estimated logical solution of the flow field, emphasizing the combined effect of magnetic forces, suction, and periodic inoculation on three-dimensional momentum transport.

Chaudhary and Pawan Kumar Sharma (2003) discussed approximately the three dimensional steady MHD Couette flow of a viscous electrically conducting fluid in which the subordinate fixed porous plate is exposed to an intermittent inoculation velocity and the higher porous plate in the continuous motion to a continuous suction velocity. Thus an estimated solution for the flow field is achieved.

Nabil et al (2005) examined the stable MHD flow of a viscoelastic fluid over a porous medium among two porous similar plates due to the effect of a crosswise magnetic field. The Brinkman–Forchheimer extension of Darcy's law was utilized, and exact solutions were derived by a perturbation technique by taking a small Forchheimer number. Heat and mass transfer behaviour were explored, and skin friction, Nusselt number, and Sherwood number expressions were found.

Jain and Gupta (2006) examined three-dimensional free convection Couette flow with transpiration cooling between parallel vertical plates. The plate was exposed to transverse sinusoidal fluid addition and the affecting plate had continuous suction. This injection suction arrangement created a three-dimensional flow field. Analytical solutions were found for speed, temperature distribution, skin friction

and heat transmission. This research gave insights into the effects of free convection, transverse suction/injection, and plate motion on flow and thermal constraints.

Three-dimensional fluctuating Couette flow with heat transmission over horizontal porous plates was studied by Guria and Jana (2006). The unstable viscous incompressible fluid flow was described by periodic pressure on the fixed plate and continuous injection on the moving plate. Approximate effects for velocity, temperature fields, expressions for skin friction associated quantities, were found with the perturbation technique. The investigation involved viscous dissipation effects on heat transfer behaviour. Findings indicated that the velocity of the core flow reduces, whereas the cross flow velocity magnitude increases, with increased frequency constraints. Same way, amplitude of the shear stress caused by the main flow reduces, whereas that by cross-flow enhances, as frequency increases. The phase shift tangent of both cross flow and main flow components was found to reduce with frequency, and temperature increased with rising frequency constraint.

Bhupendra Kumar Sharma et al (2007) conducted a hypothetical study of three-dimensional Couette flow accounting for the thermal radiation influence on temperature distribution. The fluid was injected by the lower fixed plate with a transverse sinusoidal velocity and extracted by uniform suction through the top porous plate moving uniformly, creating a three-dimensional flow. The effect of the Prandtl number, radiation constraint, inoculation constraint on the heat transfer rate was examined using graphical solutions. The Prandtl number was observed to have a controlling effect on temperature distribution.

Govindarajan, Ramamurthy and Sundarammal (2007) examined heat transmission in three-dimensional Couette movement of a viscous fluid through a compound station partly occupied with a porous medium and partly with a pure fluid. The porous medium occupied the minor part of the channel and was surrounded by a permeable plate under transverse sinusoidal injection, whereas the top part had clear fluid and a porous moving plate at continous velocity with continuous suction. The channel plates were held at continuous but unequal temperatures. Analytical solutions were obtained to know the effects of key constraints on the temperature distribution and heat transmission rate.

Das et al (2008) explored the three-dimensional Couette flow of a viscous, electrically conducting fluid among two infinite parallel flat porous plates in the occurrence of a crosswise magnetic field. Transverse sinusoidal injection were applied to the fixed plate, and uniform motion on the uniformly moving plate had continuous suction. The governing momentum equations were explained by the series expansion technique to find analytical results for the velocity, temperature fields, skin friction, Nusselt number. The effects of different flow constraints were analysed and presented by figures and tables.

Tsukahara, Tillmarkand and Alfredsson (2010) experimentally studied flow states in plane Couette flow within a span wise rotational edge of position. The study was performed within a Couette cell placed on a rotating table with flow visualization obtained by suspending reflective flakes in water. Short and long time photographic exposures were utilized to record instantaneous turbulent structure and averaged large scale patterns. A correlation method applied to the light intensity of the images allowed objective measurement of span wise and stream wise wavelengths of the flow structures.

Sahin Ahmed and Liu (2010) discussed the issue of a three-dimensional varied convection and mass transmission flow of a viscous fluid along an immeasurable permeable perpendicular plate with continuous torrent velocity. The plate was under a crosswise sinusoidal suction velocity, which created a three-dimensional flow. Based on a series expansion technique, velocity, temperature, concentration, skin-friction, heat and mass transmission expressions were derived. It was found that increased suction constraint values decrease velocity, concentration, and mass transfer rate. As Prandtl number increases, velocity and temperature are decreased but skin friction, heat transfer rate are increased.

Ahmed (2010) explored the three-dimensional MHD free and forced convection flow of viscous, electrically conducting fluid with mass transmission over a perpendicular porous plate with crosswise sinusoidal suction. There was a constant magnetic field applied perpendicular to the free stream direction. Analytical representations of skin friction, heat and mass transmission rates were got in non-dimensional form and velocity, temperature, concentration fields were discussed. Properties of relevant constraints like the Hartmann number, Reynolds number, Schmidt number on velocity, heat, and mass transfer behaviours were discussed and physically interpreted with the help of graphical results.

Dileep Singh Chauhan and Vikas Kumar (2010) studied the Couette flow of a liquid through a compound station occupied by a porous medium. The bottom portion of the station was bounded by a porous plate, to which a crosswise sinusoidal inoculation speed was prescribed. The top portion had a clear fluid enclosed within a porous plate traveling at a speed and being exposed to continuous suction. The research analysed the influence of permeability, porous layer thickness, effective viscousness, and inoculation constraint on the flow dynamics.

Dileep Singh Chauhan and Vikas Kumar (2011) theoretically examined the heat transmission behaviours within a three-dimensional Couette flow through a compound parallel porous plate that is partly packed with a

porous medium. The three-dimensionality of the flow was triggered by a crosswise sinusoidal injection velocity imparted at the lower fixed porous plate. Perturbation series expansion technique was used to explain the main calculations. The effect of Prandtl number, suction/injection constraint, porous medium permeability, heat source constraint, and viscosity ratio was examined on the temperature distribution within the station.

Bhupendra Kumar Sharma et al (2011) discussed a solution of varied convection three-dimensional steady laminar flow of a viscous fluid along an infinite perpendicular porous plate. With uniform plate velocity assumed, exact results for velocity, temperature, skin-friction were derived.

Das and his team (2012) have studied the unstable free convection layer flow of a viscous electrically conducting sandy fluid over an imprudently started perpendicular flat plate with ramped temperature, taking into account the effect of immersion of heat and a crosswise magnetic field. A particular solution of the model for two stage flow and temperature transmission has been derived based on the Laplace transform method. This research also explored the effect of dissimilar flow strictures on the two stage flow model, and results were illustrated in terms of thorough graphical and tabular representations.

Gireesha et al (2012) developed a mathematical model for the three-dimensional Couette flow heat transmission of a dusty fluid between two infinite flat parallel porous plates with a continuum two-phase model. Transverse exponential injection at the lower plate with continuous force at the upper plate created a three-dimensional flow field. The partial differential equations governing the flow were solved systematically via perturbation technique in closed form expressions for the fluid and dust stage velocity and temperature fields. The impact of improved flow constraints on the flow and heat transmission behaviour was presented through graphical results.

Nandkeolyar and Das (2014) studied the unstable free convection border layer flow of an electrically conducting and viscous dusty fluid. Particular solutions for the two stage flow and heat transmission were determined using the Laplace transform method. To make the comparison easier, solutions were also obtained for the analogous circumstance of an isothermal plate. Nusselt number, skin friction terms were given for ramped temperature, isothermal cases.

Gupta and Jain (2016) studied the hydro magnetic Couette flow and heat transmission of an electrically conducting viscous fluid in a porous medium among two infinite flat parallel plates with injection/suction effects being taken into account. The whole channel was supposed to be rotating around a direction perpendicular to the plates. Using the perturbation method, analytical solutions of the governing non-dimensional motion and energy equations were derived. The effects like magnetic field, rotation, Prandtl number, permeability, injection/suction, heat immersion, and thermal slip on velocity, temperature, skin friction, Nusselt number were studied graphically.

Loganathan and Gomathi (2016) investigated the unstable three dimensional Couette flow of a viscous fluid among two porous flat plates under periodic suction and uniform injection. The perturbation method was utilized to find estimated analytical results for the velocity, temperature fields, skin friction, Nusselt number. Graphical plots were given to evaluate the result of changed non-dimensional constraints. The analysis indicated that increase in the mass concentration constraint increases the primary velocity, whereas an increase in the frequency constraint makes the main velocity profiles flattened.

Vineet Kumar Verma and Pawan Kumar Dixit (2017) considered the uniform flow of a viscous incompressible fluid in an annular space among two coaxial moving cylindrical tubes saturated by a porous medium with spatially adjustable permeability. Constructing with Brinkman model, exact solutions were obtained for three different permeability variation cases. Expressions for velocity distribution, volume flow rate, average velocity, and surface stresses on the cylinders were derived, together with the average permeability of the medium for the variable permeability case.

Gayathri, Govindarajan and Sasikala (2018) examined three-dimensional Couette flow and heat transmission of a dusty fluid with the effect of a crosswise magnetic field, with an exponential injection/suction constraint. Analytical results for velocity and temperature fields of the fluid, dust particle stages were found using perturbation technique. The investigation examined the impact of main constraints as dust particle mass concentration, suction rate, and Prandtl number on the primary and cross-flow velocity components. Graphical plots established the clear impact of magnetic field and injection/suction on the momentum and heat transmission behaviour of the three-dimensional dusty Couette flow system.

Niranjana et al (2020) performed an analytical study of three-dimensional steady incompressible viscous fluid flow in a porous medium bounded by parallel infinite vertical plates. Joined properties of mass transmission, first-order chemical reaction, heat transmission, and internal heat generation were considered in the study.

Muhammad Bilal et al (2021) studied the free convective Couette flow of a viscoelastic dusty fluid influenced by a crosswise constant magnetic field in a rotating frame. The fluid flow was induced by sine fluctuations of the top plate beside with the influence of free convection. Non-dimensional governing partial differential equations were derived with dimensionless variables

obtained through the application of the Buckingham–Pi theorem. The problem was solved by applying the Poincare–Lighthill perturbation method assuming periodic solutions. Analytical results for skin friction and Nusselt number were derived.

Purushottam Singh and Anil Kumar Khandelwal (2023) examined the MHD generalized plane Couette flow of a viscous fluid over a station packed with porous media of various permeability with a free surface exposed to atmospheric pressure. The flow regime was separated into three zones: zone I in the free fluid under the Navier–Stokes equations, zone II in the high-permeability zone under the Brinkman equations, and zone III in the low-permeability zone under Darcy's law.

III. NUMERICAL STUDIES

Mitra and Bhattacharyya, (1981) considered unstable laminar flow of electrically conducting viscous dusty fluid between two extremely long non-conducting similar plates below the effect of a constant crosswise magnetic field. The plates remained impulsively started from rest and afterwards accelerated with various uniform speeds. Particular results for the velocity fields of dust particles and fluid were derived as a function of concentration, relaxation time, and Hartmann number.

Nagata (1990) communicated a finite amplitude solution of plane Couette flow in the form of time-independent three dimensional structures. They solved these numerically by generalizing the bifurcation analysis of Couette flow in co-rotating cylinders with a thin hole to the limiting event of nil mean rotation rate.

Hazem and Attia (2002) examined heat transmission of a dusty magneto hydrodynamic fluid. The fluid is compelled with constant force and uniform magnetic field is applied vertically to the plates. Influence of viscosity, absorption of the fluid, constant magnetic field on velocity, temperature fields, dust particles is explained.

Hazem Ali et al (2013) investigated the momentary general Couette flow of a non-Newtonian viscoelastic fluid over a porous medium among parallel porous plates. Uniform suction at the upper plate and injection at the lower plate were applied vertically near the plates, with two different temperatures. The fluid viscosity was taken to be exponentially dependent on temperature, and the flow was generated by a horizontally uniform, exponentially decreasing pressure gradient. The coupled momentum, energy equations were numerically explained by the finite difference technique. The result for important physical constraints on the velocity and temperature distributions was examined, the results were graphically offered.

Jain and his co-workers (2013) examined the free and forced convection of a viscous fluid in a perpendicular porous station confined between moving perpendicular plates of the same velocities in opposite directions. Slip conditions were used at boundaries, while wall temperature and mass concentration were presumed to vary spanwise in the sinusoidal profile. Closed-form equations for velocity, temperature, concentration profiles, skin friction and Nusselt number were obtained.

Mosayebidorcheh and his collaborators (2014) analysed magneto hydrodynamic (MHD) Couette flow of thermal transmission of dusty fluid between parallel plates by consideration of fluid properties reliant on temperature adopting a hybrid finite difference method. Thermal conductivity in their model depended linearly on temperature and viscosity was described as an exponential function of temperature. Findings indicated that increasing Hartmann number enhances skin friction at both plates, exemplifying the major contribution of magnetic forces in Couette flow of dusty fluids.

Abbas et al (2017) solved the nonlinear governing equations of dust flows with Crank–Nicolson scheme. The numerical analysis was concerned with the impact of different physical constraints viscosity, density, conductivity, Eckert number Prandtl number on the velocity, temperature fields of both the particle and fluid phases. The findings contributed to accept the coupled behaviour of the two-phase system for different parametric variations.

Kotagiri Srihari (2017) carried out a numerical study of three-dimensional Couette flow of a viscous, electrically conducting fluid among two flat parallel porous plates with thermal radiation. A constant magnetic field was forced vertical to the flow and the heat flux were treated according to the Rosseland approximation. The problem was solved by means of an implicit finite-difference formulation in conjunction with perturbation techniques, and the computations were executed using C-programming. The research gave graphical solutions for velocity, temperature, Nusselt number for various constraint regimes, revealing that thermal radiation decreases both the temperature of the fluid and Nusselt number. Numerical solutions for Nusselt number without radiation and magnetic effects were found to agree well with previously published results.

Prasannakumaraa and his team (2017) examined the three dimensional dusty fluid behaviour and heat transmission along a stretching sheet subject to convective boundary conditions. With the use of proper similarity transformations, the main partial differential equations were changed to nonlinear ordinary differential equations. The system was solved by the Runge–Kutta–Fehlberg fourth-fifth order techniques coupled with a shooting technique. Research gave thorough descriptions of the influences of major constraints particle volume fraction, rates of stretching, and convective heating on the distributions of velocity, temperature of carrier fluid particles, thus furthering comprehension of dusty fluid transport with convective boundary constraints.

Islam and Nasrin (2021) analysed the dusty fluid's laminar heat-transferable flow between two parallel rigid plates, where the bottom plate is fixed and the top plate moves at a continuous speed. A homogeneous Lorentz force and a uniform pressure gradient were considered in the fluid. The main calculations were derived from the Navier–Stokes and energy equations with boundary-layer approximations, whereas the motion of dust particles was modelled by Newton's second law. The non-dimensionalzed calculations of velocity, temperature profiles, shear stress, Nusselt number for spotless fluid and dust particles were critically analysed.

Nasrin et al (2021) analysed a computational study of time-dependent Couette flow between two rigid plates, including Hall and ion-slip current properties. Using an explicit finite-difference technique solutions were developed for a variety of dimensionless constraints such as the pressure gradient, Hall and ion-slip, modified Hartmann number, Prandtl number, and Eckert number. Numerical results proved the significant effect of the modified Hartmann number on flow and thermal profiles.

Rajesh Kumar et al (2021) considered the unstable generalized Couette flow of immiscible fluids with heat transfer involving both dusty and pure Newtonian fluids over a firm flat stations. Three situations are investigated: (i) flow between non-porous plates with heat transmission, (ii) flow over porous plates with continuous force, injection and heat transmission (iii) flow between non-porous plates with moving liquid–liquid boundary.

Ibrahim, Yale and Gambo Musa (2022) investigated unstable magneto hydrodynamic (MHD) Couette flow in a vertically positioned porous station with thermal radiation and temperature effects. The model calculations remained reduced to non-dimensional form using standard transformations. Transient velocity, temperature, and concentration fields were numerically solved through an implicit finite difference approach. The impacts of critical constraints thermal Grashof number, modified Grashof number, Prandtl number, thermal radiation constraint, Schmidt number were discussed graphically.

Bibhash Deka (2024) studied three-dimensional unstable Couette flow of viscoelastic fluid in a porous channel among two infinite parallel plates with heat and mass transmission. The research used the second-order Rivlin–Erickson fluid model and utilized the regular perturbation technique to derive approximate velocity, temperature, concentration, and other flow variable solutions. The study emphasized the result of different constraints on movement behaviour, with their effect illustrated via graphical representation. Notably, the results for Newtonian fluids were proved to arise as limiting cases, thus establishing the validity of the generalized formulation.

IV CONCLUSION

Research in three-dimensional dust laddened Couette flow has proven that magnetic fields, rotation, porous medium characteristics, and particle interactions are significant in determining flow and heat transfer behaviour. The discoveries form a solid basis for the design of efficient multiphase industrial operations like cooling systems, filtration systems, and chemical reactors. In practical applications, performance can be maximized by strategically modulating suction and injection velocities, magnetic field strengths, and boundary heat conditions. For the greater practicality of this research, subsequent studies need to investigate nonlinear effects, incorporate turbulence modelling, and investigate complex geometries.

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