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Electro-Thermo-Hydrodynamics in Different Shaped Enclosures

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ABSTRACT:

The present study investigates the intricate interplay of electrostatic, thermal, and hydrodynamic phenomena within differently shaped enclosures, shedding light on the complex interactions that occur at the micro and nanoscales. The utilization of these phenomena holds immense potential for applications in fields such as microfluidics, electronics cooling, and energy harvesting. The research focuses on enclosures with diverse geometries, including rectangular, cylindrical, and irregular shapes, to discern the impact of geometry on electro-thermal-hydrodynamic (ETH) behaviors. A combination of theoretical modeling, numerical simulations, and experimental validations is employed to explore the nuanced dynamics of fluid flow, heat transfer, and electrokinetic effects within these enclosures.

Key objectives of the study include:

Geometry-dependent Analysis: Investigating how different shapes influence the distribution and intensity of electric fields, temperature gradients, and fluid flow patterns. This aspect aims to provide insights into optimizing geometries for enhanced performance in specific applications.

Electrokinetic Phenomena: Analyzing electro-osmotic and electrophoretic effects in the presence of thermal gradients, elucidating their role in driving fluid motion within the enclosures. This research contributes to a deeper understanding of electrokinetic transport under varied geometric configurations.

Heat Transfer Enhancement: Evaluating the impact of electrothermal effects on heat transfer within the enclosures and assessing their potential for thermal management applications. The study aims to identify optimal conditions for efficient heat dissipation or energy harvesting.

Experimental Validation: Conducting experimental investigations to validate the theoretical models and numerical simulations. The experimental work involves the use of advanced measurement techniques to quantify fluid velocity, temperature profiles, and electrostatic potential within the enclosures.

The outcomes of this research have implications for the design and optimization of systems where precise control over fluid flow, heat transfer, and electrokinetic phenomena is crucial. Potential applications include microfluidic devices, lab-on-a-chip systems, and thermal management solutions in electronic devices.

The comprehensive understanding gained from this study not only advances fundamental knowledge in electro-thermo-hydrodynamics but also opens avenues for innovative applications with broader implications across various scientific and engineering disciplines.

1.1 Porous media:

- A porous medium is a material containing pores.
- The skeletal portion of the material if often called the matrix or frame. The pores are typically filled with a fluid (liquid or gas).
- A porous medium is most often characterized by its porosity and permeability.
- Porous medium having other properties also (e.g., electrical conductivity, tensile strength)
- The study of more general behaviour of porous media involving deformation of the solid frame is called Poro mechanics.

1.1.1 Porosity:

- Porosity refers to the fraction of a porous material's volume that is composed of void spaces or pores.
- It is expressed as a percentage and indicates how much empty space exists within the material.
- High porosity means more available space for fluid storage.

1.1.2 Permeability:

- Permeability measures how easily fluids can flow through porous media.
- It is influenced by the size, shape, and connectivity of the pores.
- Permeability is a critical property for understanding fluid transport, and it can vary significantly between different porous materials.

1.1.3 Darcy's Number:

- It is a dimensionless quantity used in fluid dynamics to characterize the flow of fluid through a porous medium, such as a rock or soil.
- $Da = (K/L^2)$
  Where:
  Da - Darcy number (dimensionless).
  K is the permeability of the porous medium (m^2)
- *L* is the characteristic length or thickness of the porous medium (measured in meters or feet).
  μ is the dynamic viscosity of the fluid (measured in units like Pa.s or centipoise).

1.2 Applications of porous media:

- Groundwater and Hydrogeology
- Filtration and Separation
- Oil and Gas Reservoirs
- Energy Storage
- Food Industry

1.3 Nanofluid:

- A nanofluid is **a fluid containing nanometre-sized particles, called nanoparticles.**
- The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes.
- Common base fluids include water, ethylene glycol and oil.

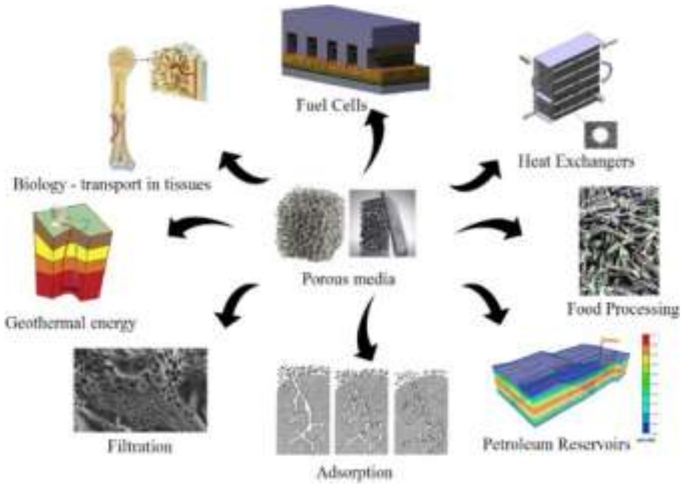


Fig 1.1 Applications of nanofluid

1.3.1 Hybrid Nanofluid:

- Different types of nanoparticles added in one base fluid called as hybrid nanofluid.

- Due to different nanoparticles heat convection process is more.

1.4 Applications of hybrid nanofluid:

- Enhanced Performance
- Multi-Functionality
- Efficient Heat Transfer
- Environmental Remediation

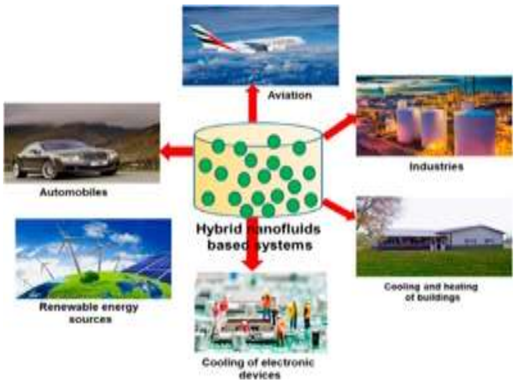


Figure 1.2 Applications of hybrid nanofluid

1.6 Electro-thermo-hydrodynamics (ETHD):

- This study that combines principles from electrostatics, thermodynamics, and hydrodynamics to investigate the behavior of fluids.
- ETHD plays a critical role in optimizing processes, improving energy efficiency, and developing innovative technologies across multiple fields.
- EHD (Electro hydrodynamics) is a subset of ETHD that focuses on the interaction between electric fields and fluid flow.

1.6.1 Electric Rayleigh number (T):

- It is a dimensionless number used to describe the stability of a dielectric fluid layer subjected to an electric field.
- This dimensionless number is important in the field of electro hydrodynamics, which studies the behavior of electrically conducting or dielectric fluids under the influence of electric fields.
- The electric Rayleigh number is used to assess the relative importance of buoyancy forces to electric forces in the context of electrohydrodynamic instabilities.

1.7 Applications of ETHD:

- Heat transfer enhancement
- Electrokinetic energy conversion
- Electrokinetic propulsion
- Energy storage and conversion

1.8 Magneto Hydrodynamics (MHD):

- It is a multidisciplinary field of study that combines principles from both magnetism and fluid dynamics to investigate the behavior of electrically conducting fluids (such as plasmas, liquid metals, or ionized gases) in the presence of magnetic fields.
- MHD plays a crucial role in magnetic confinement fusion experiments, which aim to replicate the nuclear fusion reactions that power the sun and stars.

- MHD can be used to generate electricity directly from the motion of an electrically conducting fluid in a magnetic field, a process known as magnetohydrodynamic power generation.

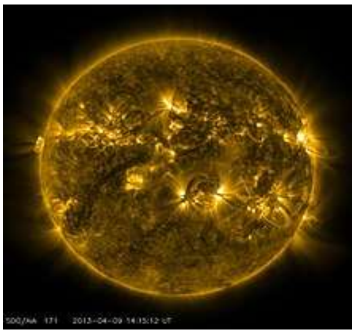


Figure 1.1. magneto hydrodynamics (MHD)

1.8.1 Hartmann number (Ha):

- It is a dimensionless number used in the field of magnetohydrodynamics (MHD) to describe the relative importance of electromagnetic forces (Lorentz forces) to viscous forces in the flow of an electrically conducting fluid, such as a plasma, liquid metal, or ionized gas, in the presence of a magnetic field.
- $Ha = B * L * \sqrt{(\sigma / \mu)}$
  where,

Ha is the Hartmann number (dimensionless).
B is the magnetic field strength.
L is a characteristic length (e.g., a characteristic dimension of the system).
σ is the electrical conductivity of the fluid.
μ is the dynamic viscosity of the fluid

1.9 Applications of MHD:

- Magnetic confinement fusion
- Magnetic flow control
- Aerospace and propulsion
- Space exploration

[1] Fazlollahi and A.A.Alemrajabi

Author1: Fazlollahi and Author2: A.A.Alemrajabi

Title: Electro-thermo-convection in non-Newtonian power-law fluids within rectangular enclosures

The study investigates the electro-thermo-convection specifically considering differentially heated vertical and horizontal wall configuration. The top moving wall with uniform velocity (u=1, v=0). The simulations are carried out for four typical power-law indexes of n=0.25, 0.5, 1.0, and 1.5 .

Result:

The paper considers two different geometrical configurations: differentially heated vertical walls (DHVW) and differentially heated horizontal walls (DHHW). The Nusselt number, which represents the heat exchange intensity of the system, is studied as the temperature (T) is varied. For the DHVW configuration, the paper finds that an increase in T causes the heat exchange intensity to increase continuously.

The heat transfer characteristics between horizontal and vertical plates depend on several factors, including the mode of heat transfer, the boundary conditions, and the specific configuration of the system.

However, in many cases, natural convection on vertical plates tends to be more effective due to the natural upward flow of the fluid, promoting better heat transfer. In forced convection, horizontal plates often exhibit higher heat transfer rates compared to vertical plates, as the forced flow is more aligned with the plate surface.

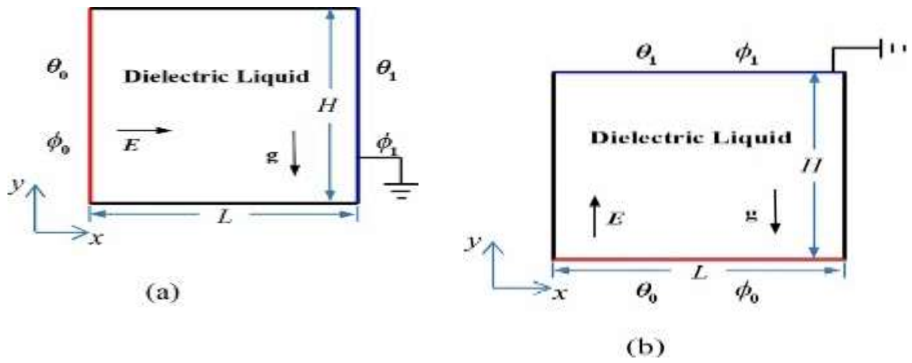


Fig. 1. Geometrical configuration of electro-thermo-convection: (a) differentially heated vertical walls (DHVW); (b) differentially heated horizontal walls (DHHW).

[2] Ma, Ben, et al.

Author1:ma and Author2: Ben

Title: Electro-thermo-capillary-convection in a square layer of dielectric liquid subjected to a strong unipolar injection.

In this paper study on electro-thermo-capillary convection in a dielectric liquid subjected to a Strong unipolar injection different values of Marangoni number ($-10000 \leq Ma \leq 10000$), thermal Rayleigh number ($5000 \leq Ra \leq 50000$) and electric Rayleigh number ($0 \leq T \leq 800$). The Prandtl number (*Pr*) and the mobility parameter (*M*) are fixed at 116.6 and 49, respectively.

Result:

Temperature gradients affect surface tension gradients, leading to thermocapillary effects in fluid motion. The paper investigates the combined effect of electric field, buoyancy, and thermocapillary forces on the flow .The temperature field is studied in the numerical simulation, showing the influence of temperature on the flow structure and heat transfer .Increasing the thermal Rayleigh number improves heat transfer.

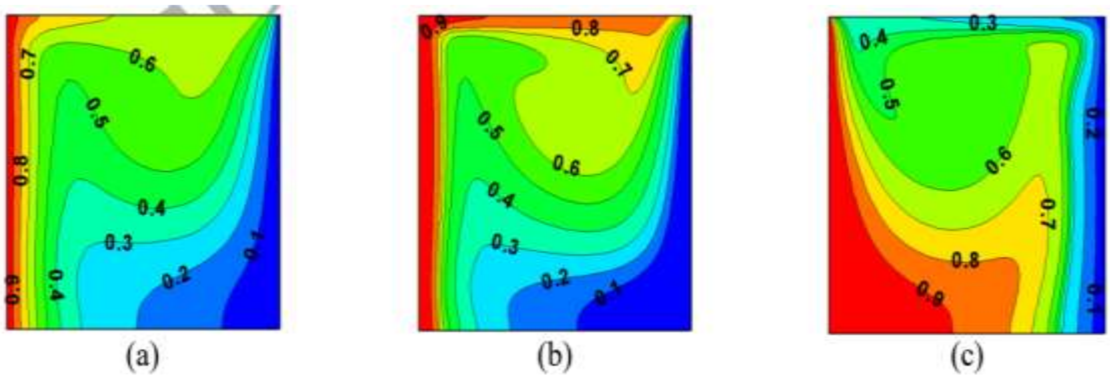


Fig. 2. Representation of isotherms for $Ra = 10^4$ and $Ma = 5000$, (a) without injection (b) left injection with $T = 600$, (c) right injection with $T = 600$

[3] Yan, Y. Y, H.B. Zhange, and J.B.Hull

Author1: Yan Author2: Y.Y

Title: Numerical analysis of the subcritical feature of electro-thermo-convection in a plane layer of dielectric liquid

This paper reports a numerical investigation with a horizontal layer of dielectric liquid subjected to the simultaneous effects of external thermal and electric fields. The flow is driven by the buoyancy force and the Coulomb force, which depend on the Rayleigh number (Ra) and the electric Rayleigh number (***T***). It is shown to be independent on the Prandtl number (Pr) and the dimensionless mobility number (M).

Result:

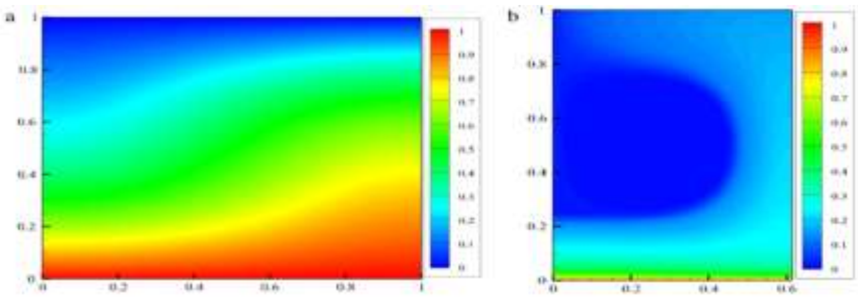


Fig. 3. Iso-contour plots of (a) temperature distribution for Rayleigh–Benard convection with Ra = 2000 and Pr = 10; (b) charge density distribution for electro-convection with T = 200 and M = 10.

[4] Luo, Kang, et al.

Author1:Luo and Author2:kang.

Title: Electro-thermo-convective flow of a dielectric liquid due to nonautonomous injection of charge by an elliptical electrode

The paper investigates the electro-thermo-hydrodynamic (ETHD) flow in a dielectric medium induced by Coulomb and buoyancy forces, considering nonautonomous charge injection from an elliptical electrode to parallel-plate electrodes. The simulations also analyze the influences of the curvature of the inner electrode (ellipticity) on injection strength and its consequent effects on ETHD flow and heat transfer enhancement. parameters including electric Rayleigh number (300 < T < 1800), Rayleigh number (103 <Ra < 107) and the ellipticity(e=2) of the elliptical electrode.

Result:

For the left and right boundaries, a periodic boundary condition is used, which assumes that a particle leaves the computational domain from one side and re-enters from the opposite side. This means that the fields at the left and right boundaries are set to be equal to the fields at the opposite boundaries.

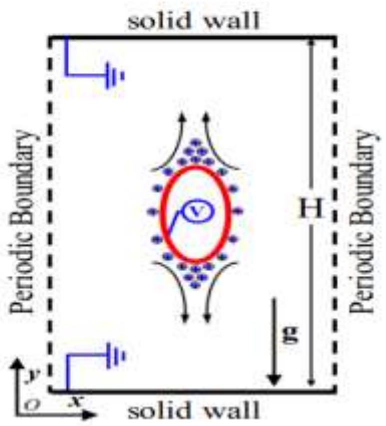


Fig.[4]. Sketches of a periodic unit of periodically arranged elliptical cylinders between two parallel plates.

[5] Futterer, Birgit, Norman Dahley, and Christoph Egbers.

Author1: Futterer Author2: Birgit.

Title: Numerical mode ling of the electrohydrodynamic effect to natural convection in vertical channels.

The paper investigates the electrohydrodynamic effect on natural convection in vertical channels using computational fluid dynamics. The study considers a range of parameters such as Rayleigh number(10^4<Ra<10^7).voltage at the wire electrodes (7.5 =V0= 17.5 kV), and aspect ratio (10). The results show that the flow and temperature distributions are influenced by the supplied voltage, and heat transfer enhancement is significant at low Rayleigh numbers. The volume flow rate of the fluid is also affected by the number of electrodes, and the heat transfer enhancement depends on the electrode arrangement. The paper provides insights into the relationship between channel aspect ratio, number of electrodes, and maximum heat transfer.

Result:

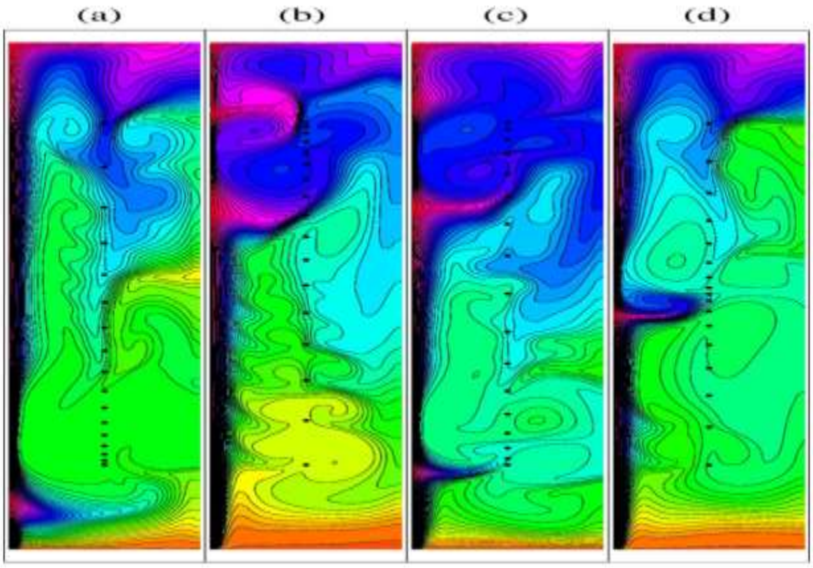


Fig. 5. Temperature distributions of various electrode arrangements (V0= 17.5 kV, Ra= 106 and N=17) (a) bottom denseness, (b) top denseness, (c) ends denseness, (d) middle denseness

(a) The term "bottom denseness" refers to a parameter or characteristic related to the density of the fluid at the bottom of the vertical channel. It is one of the factors being considered in the numerical investigation of the electrohydrodynamic effect to natural convection.

(b) Similarly, "top denseness" refers to a parameter or characteristic related to the density of the fluid at the top of the vertical channel. It is another factor being considered in the numerical investigation.

(c) The term "aspect ratio" is given as 2. It represents the ratio of the height to the width of the vertical channel. The relationship between the aspect ratio and the number of electrodes that results in the maximum heat transfer is being expressed.

(d)The term "heat transfer enhancement" refers to the increase in the rate of heat transfer due to the electrohydrodynamic effect and the influence of the supplied voltage and electrode arrangement. The paper investigates how this enhancement is influenced by the parameters mentioned above, particularly at low Rayleigh numbers.

[6]. Mayan, Yohay, and Yuri Feldman

Author1:

Title: Thermo-electro-hydrodynamic instabilities in a dielectric liquid under microgravity.

The paper performs a linear stability analysis of a dielectric fluid under microgravity conditions, considering a radial temperature gradient and a high alternating electric field. witch are found to be independent of the Prandtl number but dependent on the curvature of the system.

Result:

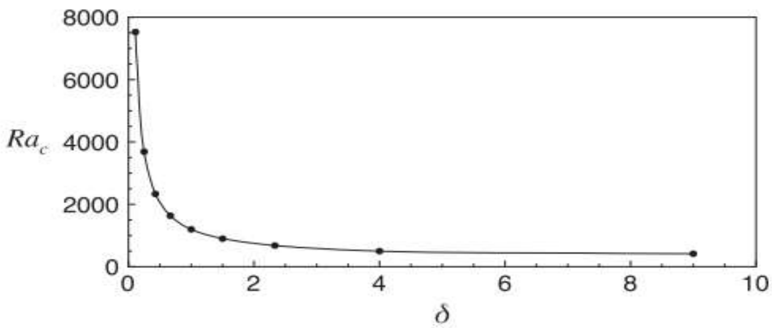


Fig. 6. Variation of critical electric Rayleigh number Rac with the curvature d

The figure illustrates how the critical electric Rayleigh number changes as the curvature of the system varies. The critical electric Rayleigh number is a dimensionless parameter that represents the onset of instability in the system.

The critical Grashof number and critical Kayleigh number are parameters that determine the onset of instability in the system.

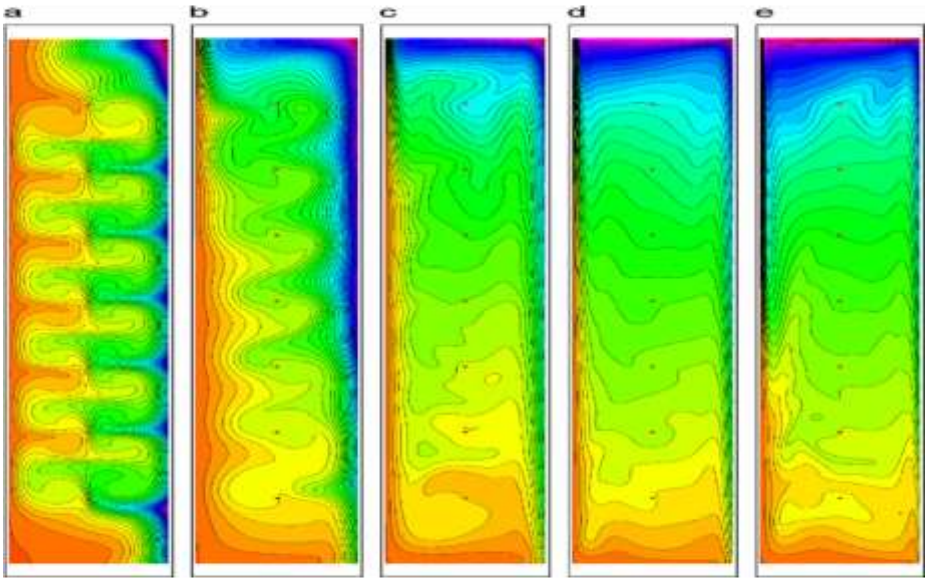
The Prandtl number is a dimensionless number that represents the ratio of momentum diffusivity to thermal diffusivity in the fluid.

[7]. Huang, Meirong, and Feng C.

Author1:Huang and Author2:Meirong ect.

Title: Numerical modeling of the effect of number of electrodes on natural convection in an EHD fluid.

The paper investigates the effect of the number of electrodes on natural convection in enclosures using numerical modeling and computational fluid dynamics techniques. The interactions between the electric field, flow field, and temperature field are analysed, and it is found that the fluid velocity and heat transfer coefficient are significantly increased with a large number of electrodes.



Fgi.7. Temperature distributions inside enclosure for various Rayleigh numbers (V_0 ¼ 17.5kV, N ¼ 7): (a) Ra ¼ 10^4, t¯ ¼ 15;000, y¼ 1.010^2, (b) Ra ¼ 10^5, ¯t ¼ 15;000, y¼ 4.010^3, (c) Ra ¼ 10^6, t¯ ¼ 15;000, y¼ 2.610^3, (d) Ra ¼ 10^7, t¯ ¼ 15;000, y¼ 1.710^3, and (e) Ra ¼ 10^8, t¯ ¼ 15;000, y¼ 9.110^4.

In this context, natural convection refers to the movement of fluid caused by temperature differences within the fluid itself, without any external forces or pumps.

The electrohydrodynamic effect refers to the interaction between an electric field and the flow and temperature fields in the fluid. In this study, the researchers are investigating how the electric field affects the flow pattern and temperature distribution in an enclosure.

The voltage supplied at the wire electrodes is the electric field that is applied to the fluid. The researchers found that this voltage has a substantial impact on the flow pattern and temperature distribution, especially at low Rayleigh numbers. The Rayleigh number is a dimensionless number that represents the ratio of buoyancy forces to viscous forces in the fluid.

The researchers also found that the fluid velocity and heat transfer coefficient (a measure of how efficiently heat is transferred) are significantly increased when a large number of electrodes is used. However, they observed that there is a minimum value of augmented heat transfer that occurs with an intermediate number of electrodes. This means that there is an optimal number of electrodes that leads to the maximum enhancement of heat transfer.

CONCLUSION:

In conclusion, the investigation into electro-thermo-hydrodynamics within various enclosures has yielded valuable insights into the complex interplay of electrical, thermal, and fluid dynamic phenomena. The study focused on understanding how different enclosure shapes influence these interactions and has provided significant findings with implications for both theoretical understanding and practical applications.

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