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Entropy Generation and Dissipative Effects on Couette Flow in an Aligned Magnetic Field with Radiation and Heat Source

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Abstract:*The Aim Of This Paper Is To Study The Entropy Generation In Steady Couette Flow Bounded Below By A Permeable Bed In The Presence Of Aligned Magnetic Field, Heat Source/Sink, Thermal Radiation, Viscous Dissipation And Joules Dissipation. The Equations Governing The Flow Are Solved Analytically And The Impact Of Various Flow Parameters On Velocity, Temperature And Entropy Generation Has Been Analyzed Through Graphs. The Shear Stress And Rate Of Heat Transfer Coefficients At The Channel Walls Are Derived And Their Behavior Was Discussed Through Tables. It Has Been Found That The Flow Parameters Considerably Affect The Flow Characteristics.*
Keywords: *Entropy, Couette Flow, Aligned Magnetic Field, Radiation, Heat Source, Dissipation*

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I. Introduction

The Study Of Fluid Flow And Heat Transfer In A Porous Channel Has Received Considerable Attention During The Last Several Decades Due To Their Relevance In A Wide Range Of Engineering And Biological Settings Such As Ground Water Hydrology, Irrigation And Drainage Problems And Also In Absorption And Filtration Processes In Chemical Engineering. Rapid Progress In Science And Technology Has Led To The Development Of Increasing Number Of Flow Divisors That Involve The Manipulation Of The Fluid Flow In Various Geometry. Many Text Books Of Fluid Dynamics Fail To Mention But The No Slip Condition Remains An Assumption Due To Unusual Agreement For A Century. Nevertheless Another Approach Supposed That Fluid Can Slide Over A Solid Surface Because The Experimental Fact Was Not Always Accepted In The Past. Navier [1] Proposed General Boundary Conditions Which Include Possibility Of Fluid Slip At The Solid Boundary. He Proposed That The Velocity At A Solid Surface Is Proportional To The Shear Stress At The Surface. The Phenomenon Of Slip Occurrence Has Been Demonstrated By The Recent Theoretical And Experimental Studies Such As [2 -6].

In Fluid Dynamics Couette Flow Refers To The Laminar Flow Of A Viscous Fluid Between Two Parallel Plates One Of Which Is Moving Relative To The Other. This Type Of Flow Is Named In Honor Of Maurice Marie Alfred Couette, A Professor At The French University Of Angers In The Late 19th Century [7]. Couette Flow Occurs In Fluid Machinery Involving Moving Parts And Is Especially Important For Hydrodynamic Lubrication Was Presented By Yasutomi Et Al. [8]. Couette Parallel Plate Channel Flow Is A Classical Problem In Fluid Dynamics Which Offers Analytical Solution To Highly Nonlinear Navier-Stokes Equations For Constant Fluid Property Fluids And Undoubtedly Serves As An Important Idealized Configuration To Peep Into Rather More Complex Real World Systems. Though, In The Present Scenario Of Digital World Where One Has Advantage Of State Of Art Numerical Techniques And Softwares, The Analytical Solutions May Not Sound That Much Lucratively Big Thing But One Has To Acknowledge The Fact That There Are Very Few Flow Problems In Fluid Dynamics Which Are Amenable To Closed Form Solution. Analysis Of Flow Formation In Couette Motion As Predicted By Classical Fluid Mechanics Was Presented By Schlichting And Gersten [9]. Other Works On Fluid Flow Induced By Moving Boundaries In Channels Are Studied By [10-15].

The Foundation Of Knowledge Of Entropy Generation Goes Back To Clausious And Kelvins Studies On The Irreversibility Aspects Of The Second Law Of The Thermo Dynamics. However, The Entropy Generation Resulting From Temperature Differences Has Remained Untreated By Classical Thermodynamics. The Second Law Analysis Is Important Because It Is One Of The Methods Used For Predicting The Performance Of The Engineering Processes. The Second Law Of Thermodynamics Is Applied To Investigate The Irreversibilities In Terms Of The Entropy Generation Rate. Since Entropy Generation Is The Measure Of The Destruction Of Available Work Of The System, The Determination Of The Active Factors Motivating The

Entropy Generation Is Important In Upgrading The System Performances. Entropy Generation Minimization Studies Are Vital For Ensuring Optimal Thermal Systems In Contemporary Industrial And Technological Fields Like Geothermal Systems, Electronic Cooling, Heat Exchangers To Name A Few. All Thermal Systems Confront With Entropy Generation. Entropy Generation Is Squarely Associated With Thermodynamic Irreversibility. Bejan [16-19] Presented A Method Named Entropy Generation Minimization (EGM) To Measure And Optimize The Disorder Or Disorganization Generated During A Process Specifically In The Fields Of Refrigeration (Cryogenics), Heat Transfer, Storage And Solar Thermal Power Conversion. A Study Of Entropy Generation In Fundamental Convective Heat Transfer Was Studied By Bejan [20]. Chauhan And His Coworkers [21-23] Discussed Entropy Generation In Different Configurations. Chinyoka And Makinde [24] Studied Analysis Of Entropy Generation Rate In An Unsteady Porous Channel Flow With Navier Slip And Convective Cooling. Analysis Of Entropy Generation And Convective Heat Transfer Of Al_2O_3Nanofluid Flow In A Tangential Micro Heat Sink Was Reported By Amir Shalchi Tabrizi [25]. Baag Et Al. [26] Have Studied Entropy Generation Analysis For Viscoelastic MHD Flow Over A Stretching Sheet Embedded In A Porous Medium. Basant Et Al. [27] Investigated Natural Convection Flow Of Heat Generating/Absorbing Fluid Near A Vertical Plate With Ramped Temperature. Vyas [28] Investigates The Entropy Generation In Radiative Dissipative Couette Flow Of A Newtonian, Incompressible Electrically Conducting Fluid In A Parallel Plate Channel Whose Upper Impermeable Wall Moves With Uniform Velocity Whilst The Lower Wall Is Stationary And Naturally Permeable. It Is Found That The Rising Values Of Slip Coefficient And Brinkman Number Increases The Entropy Generation Number.

II. Formulation Of The Problem

ASteady Flow Of A Newtonian Optically Thick Viscous Incompressible Fluid Between Two Infinite Horizontal Parallel Plates Separated By A Distance *H*has Been Considered. The Upper Plate Moves With A Uniform Velocity u_0 Inthe Direction Of The Fluid Flow. A Uniform Transverse Magnetic Field Of Strength B Is Applied Normal To The Fluid Flow Direction. A Cartesian Coordinate System Is Chosen With x-Axis Along The Lower Stationary Permeable Surface And The Y-Axis Normal To The Plates (See Figure1). It Is Assumed That The Channel Is Long Enough In $X-$Direction.The Flow Is Fully Developed Hydro Dynamically And Thermally.Pressure And Buoyancy Forces Are Neglected.Induced Magnetic Field And Applied Electric Filed Are Also Neglected.The Temperatures Of The Lower And Upper Plates Are T_1 And T_2 Respectively, Where $T_2 > T_1$.Viscous Dissipation, Joules Dissipation And Heat Generation/Absorption Effects Are Taken Into Account.The Radiative Heat Flux In The Energy Equation Is Assumed To Follow Rosseland Approximation.Under The Above Assumptions The Governing Momentum And Energy Equations For A Steady Flow Of Viscous Incompressible Fluid Are

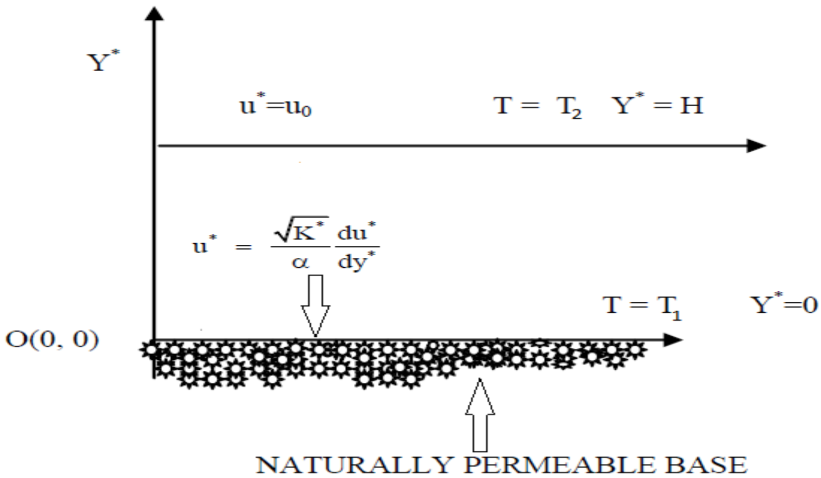

Figure 1 Physical Model Of The Problem.

$$\mu \frac{\partial^2 u^*}{\partial y^{*2}} - \sigma B^2 \sin^2 \phi \, u^* = 0 \qquad (1)$$

$$k\frac{\partial^2 T^*}{\partial y^{*2}}+\mu\left(\frac{\partial u^*}{\partial y^*}\right)^2+\sigma B^2\sin^2\phi\, u^{*2}-\frac{\partial q_r^*}{\partial y^*}+Q_1(T-T_1)=0 \qquad (2)$$

The Boundary Conditions Are

$$\left.\begin{aligned} y^*=H:&\quad u^*=u_0,\quad T^*=T_2\\ y^*=0:&\quad \frac{\partial u^*}{\partial y^*}=\frac{\alpha}{\sqrt{k}}u^*,\quad T^*=T_1\end{aligned}\right\} \qquad (3)$$

Where μ Is Dynamic Viscosity, k Is Thermal Conductivity, K^* Is Permeability, T_1 Is The Temperature Of The Lower Boundary, T_2 Is The Temperature Of The Upper Boundary, H Is The Width Of The Channel., B Is Magnetic Field Intensity, σ Is The Electric Conductivity, Q_1 Is Heat Source Parameter, ϕ Is The Aligned Angle.

The Radiation Heat Flux q_r In The Energy Equation Is Assumed To Follow Rosseland Approximation And Is Given By

$$q_r=\frac{-4\gamma^*}{3\alpha^*}\frac{\partial T^4}{\partial y^*} \qquad (4)$$

Where γ^*, α^* Are Stephan-Boltzman Constant And Mean Absorption Constant Respectively. We Assume That The Temperature Difference Within The Fluid Is Sufficiently Small So That T^4 May Be Expressed As A Linear Function Of Temperature About T_1 And Omitting Higher Order Terms To Yield

$$T^4\cong 4T_1^3T-3T_1^4 \qquad (5)$$

We Introduce The Following Non- Dimensional Quantities

$$u=\frac{u^*}{u_0},\ \theta=\frac{T-T_1}{T_2-T_1},\ y=\frac{y^*}{H},\ K=\frac{K^*}{H^2},M^2=\frac{\sigma B^2H^2}{\mu},Br=\frac{\mu u_0^2}{k\left(T_2-T_1\right)},N=\frac{4\gamma^*T_1^3}{\alpha^*k}$$

$$Q_0=\frac{H^2}{k}Q_1 \qquad (6)$$

In View Of Equations (4)-(6) The Equations (1) And (2) Become

$$\frac{d^2u}{dy^2}-M^2(\sin^2\phi)u=0 \qquad (7)$$

$$\left(1+\frac{4N}{3}\right)\frac{d^2\theta}{dy^2}+Br\left(\frac{du}{dy}\right)^2+BrM^2(\sin^2\phi)u^2+Q_0\theta=0 \qquad (8)$$

The Corresponding Boundary Conditions In Non-Dimensional From Are

$$\left.\begin{aligned} u=\frac{\sqrt{k}}{\alpha}\frac{du}{dy},\quad \theta=0\quad &at\quad y=0\\ u=1,\quad \theta=1\quad &at\quad y=1\end{aligned}\right\} \qquad (9)$$

Where*br*is Brinkman Number, Q_0 Is Heat Source Parameter $(Q>0)$ And*n* Is Radiation Parameter.

III. Entropy Generation

All Thermal Systems Confront With Entropy Generation. Entropy Generation Is Squarely Associated With Thermodynamic Irreversibility. It Is Imperative To Determine The Rate Of Entropy Generation In A System. The Convection Process In A Channel Is Inherently Irreversible And This Causes Continuous Entropy Generation. The Local Volumetric Rate Of Entropy Generation For A Viscous Incompressible Conducting Fluid In The Presence Of Magnetic Field, Thermal Radiation And Viscous And Joules Dissipation Is Given By Woods [29] And Arpaci [30].

$$E_G = \frac{k}{T_1^2}\left[\left(\frac{\partial T^*}{\partial y^*}\right)^2 + \frac{16\gamma^* T_1^3}{3k\alpha^*}\left(\frac{\partial T^*}{\partial y^*}\right)^2\right] + \frac{\mu}{T_1}\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \frac{\sigma B^2 \sin^2\phi\, u^{*2}}{T_1} \tag{10}$$

The First On The RHS (8) Is The Local Entropy Generation Due To Heat Transfer, The Second Term Is The Local Entropy Generation Due To Radiation, The Third Term Is The Local Entropy Generation Due To Viscous Dissipation And The Fourth Term Is The Local Entropy Generation Due To Joules Dissipation.

The Characteristic Entropy Generation Rate And Generation Ratio Are Given By

$$E_{G_0} = \frac{k(T_2 - T_1)^2}{H^2 T_1^2}$$ = (Characteristic Entropy Generation Rate)

$$\omega = \frac{T_1}{T_2 - T_1}$$ = (Characteristic Temperature Ratio)

The Entropy Generation Number In Terms Of The Dimensionless Velocity And Temperature Is

$$Ns = \frac{E_G}{E_{G_0}} = \left(1 + \frac{4}{3}N\right)\left(\frac{d\theta}{dy}\right)^2 + Br\omega\left[\left(\frac{du}{dy}\right)^2 + M^2(\sin^2\phi)u^2\right] = HTI + FFI \tag{11}$$

Where *Hti*is The Heat Transfer Irreversibility And *Ffi*is The Dissipative Irreversibility.
The Bejan Number Be Is The Pertinent Irreversibility Parameter And Is Defined As

$$Be = \frac{HTI}{N_s} \tag{12}$$

Where $Be = 1$, At Which Heat Transfer Irreversibility Dominates, $Be = 0$ At Which Fluid Friction Irreversibility Dominates And $Be = 1/2$ Implies That Both Of Them Contribute Equally.

IV. Solution Of The Problem

Solving The Equations (7) And (8) Subjected To The Boundary Conditions (9), The Velocity And Temperature Distributions Are Obtained As Follows

$$u = c_1 e^{M_1 y} + c_2 e^{-M_1 y} \tag{13}$$

$$\theta = c_3 \cos(m_1 y) + c_4 \sin(m_2 y) + c_5 e^{2M_1 y} + c_6 e^{-2M_1 y} \tag{14}$$

The Velocity And Thermal Regimes Obtained Are Used In (11) To Obtain The Entropy Regime.

The Skin Friction Across The Channel's Wall Is Given By

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0,\quad y=1} \tag{15}$$

The Rate Of Heat Transfer Across The Channel's Wall Is Given By

$$Nu = \left(-\frac{\partial \theta}{\partial y}\right)_{y=0,\, y=1} \tag{16}$$

V. Results And Discussion

The Effects Of Various Parameters Such As Hartmann Number M , Brinkman Number Br , Radiation Parameter N , Permeability Parameter *K*, Dimensionless Empirical Constant α , Aligned Angle ϕ , Characteristic Temperature Ratio ω And Heat Source Parameter Q Are Examined On The Velocity, Temperature, Bejan Number And Entropy Generation. The Closed Form Solution Obtained For Velocity And Temperature Are Employed To Compute The Entropy Generation. The Findings Are Depicted Through Graphs.The Variations In Velocity u And Temperature θ Distributions For Different Values Of Hartmann Number M Are Shown In Fig.2 And 3. We Observe That The Velocity u Is Decreases With Increasing Hartmann Number M . This Is Because In The Presence Of Applied Magnetic Field There Is Retardation Force Known As Lorentz Force, Which Has A Tendency To Decelerate The Fluid Motion Within The Boundary Layer. Hence, We Conclude That The Stronger Magnetic Field Causes To Reduce The Momentum Boundary Layer Thickness Whereas The Opposite Behavior Is Observed On Temperature Distribution. Figures4 And 5

Illustrate The Variations Of Velocity u And Temperature θ For Different Values Of Aligned Magnetic Field Parameter ϕ. It Is Evident From The Figure 4 That The Increasing Value Of Aligned Angle Reduces The Velocity Profiles. This May Happen Due The Reason That An Increase In Aligned Angle Strengthens The Applied Magnetic Field. But Anopposite Phenomena Is Observed On Temperature Profiles. The Variations In Temperature θ For Different Values Of Brinkman Number Br Are Presented In Fig.6. We Observe That The Temperature θ Increases With Increasing Brinkman Number Br. This Is Because The Improvement In Brinkman Number Results In Enhanced Convective Transport. The Impact Of Radiation Parameter N On Dimensionless Temperature Is Shown In Fig.7. It Is Seen That The Rising Values Of Radiation Parameter Depreciates The Fluid Temperature. Consequently, The Thermal Boundary Layer Becomes Smaller. This Result Is Quite Significant For The Flow And Heat Transfer At High Operating Temperature.

The Variation In Entropy Generation Number Ns For Different Values Of Hartmann Number M, Dimensionless Empirical Constant α, Aligned Angle ϕ,Brinkman Number Br, And Characteristic Temperature Ratio ω Are Shown In Figures 8-12. We Observe That The Entropy Generation Number Ns Increases With Increasing Values Of Hartmann Number M, Dimensionless Empirical Constant α, Brinkman Number Br, Aligned Angle Φ And Characteristic Temperature Ratio ω. From Figure 8 We Have Seen That The Entropy In The Channel Arises With Increasing Values Of M. This Reduction Is Caused As The Transversely Applied Magnetic Field Retards The Flow And Ohmic Dissipation Leads To Considerable Rise In Temperature In The Channel With Increasing Values Of M. From Fig.9 We Have Seen That The Entropy In The Channels Rises With Increasing Values Of α And This Worth Noting α Depends On Non-Uniformities In The Arrangement Of Solid Material At The Surface, Hence Materials Permeability Or Same Bulk Porosity Exhibit Different Values Of α. Entropy Generation May Be Controlled By Adjusting Values Of α Without Compromising The Permeability Of The Permeable Base. Hence Slip Coefficient Can Serve As A Pertinent Entropy Controlling Parameter In Thermal System Of Interest. From Fig.10 We Have Seen That The Entropy In The Channels Increases With Increasing Values Of Br. It Is Emphasized That Br Is A Measure Of Fluid Friction In The Dissipative Flow System. Larger Values Of Br Are Indicative Of Larger Frictional Heating In The System. Thus Br Contributes Significantly In Entropy Generation As One Of The Pertinent Fluid Friction Irreversibility Parameter. Fig.11 Displays The Effect Of Characteristic Temperature Ratio ω On Entropy Generation. It Shows That The Entropy In The Channels Raises With The Increasing Values Of ω. Figure 12 Elucidates The Effect Of Aligned Angle ϕ On Entropy Generation. It Shows That Entropy Accelerates In The Channels With The Increasing Values Of ϕ. Influence Of Characteristic Temperature Ratio ω On Bejan Number Is Shown In Figure 13. From This Figure It Is Noticed That The Bejan Number Be Decreases With Increasing Values Characteristic Temperature Ratio ω.

The Numerical Values Of Friction Factor Coefficient And The Rate Of Heat Transfer Coefficient Is Presented In Tables 1-2. From Table 1 It Is Interesting To Note That The Nusselt Number Decreases With An Increase In MOr K At Both The Plates.From Table 2, It Is Noticed That The Friction Factor Coefficient Decreases With Increasing Values Of Permeability Parameter K And An Opposite Trend Is Found With Increasing Values Of Dimensionless Empirical Constant α At Both Plates. Increasing Magnetic Field Parameter MOr Aligned Magnetic Field Parameter ϕ Suppresses The Skin Friction At The Wall Y = 0 Whereas It Enhances At The Wall Y =1.If Inclined Angle $\phi = \frac{\pi}{2}$ These Results Are In Good Agreement With The Results Of Sukumar And Varma [31].

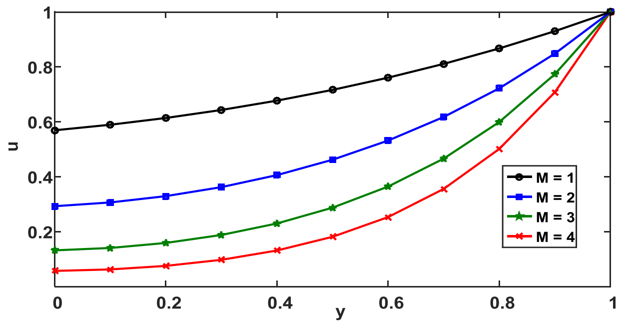

Figure 2: Velocity Profiles For Different M When $A = 0.01$, $\phi = \dfrac{\pi}{3}$ And $K = 0.001$

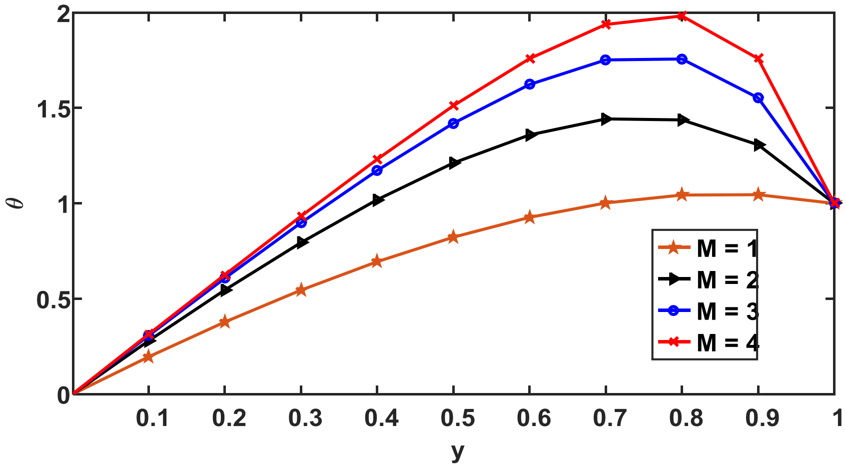

Figure 3: Temperature Profiles For Different M When $A = 0.01$, $Br= 10$, $Q= 0.1$, $N= 1$, $K = 0.001$ And $\phi = \dfrac{\pi}{3}$

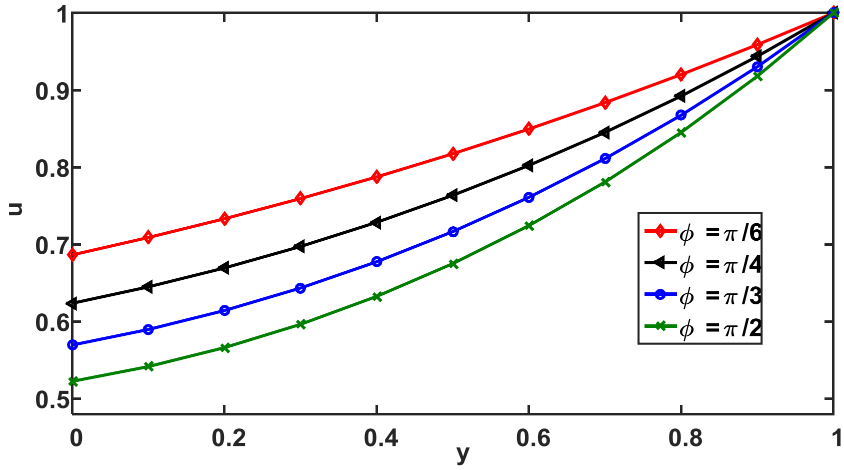

Figure 4: Velocity Profiles For Different ϕ When $M = 1$, $A = 0.01$ And $K = 0.001$

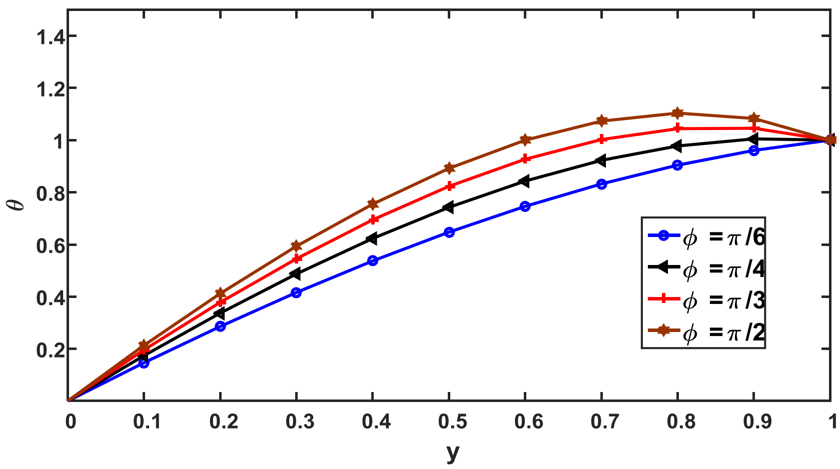

Figure 5: Temperature Profiles For Different ϕ When $M = 1$, $N = 1$, $Br= 10$, $A = 0.01$, $Q= 0.1$ And $K = 0.001$

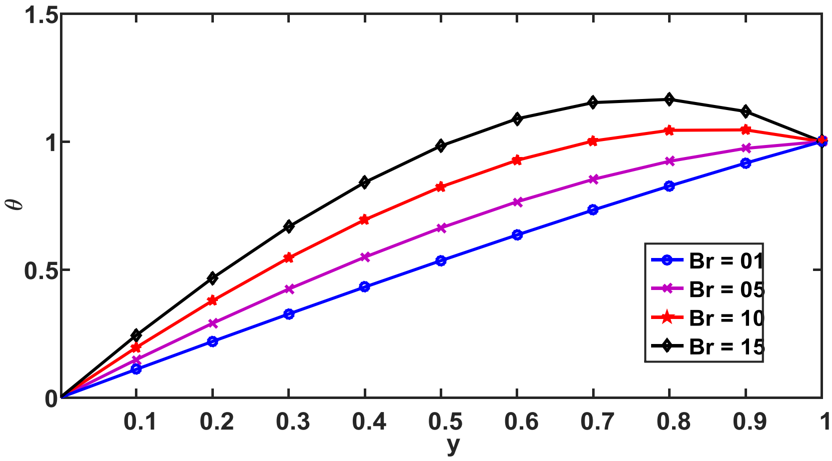

Figure 6: Temperature Profiles For Different *A* When M = 1, *A* = 0.01, *Q*= 0.1, $\phi = \frac{\pi}{3}$, *N*= 1 And *K* = 0.001

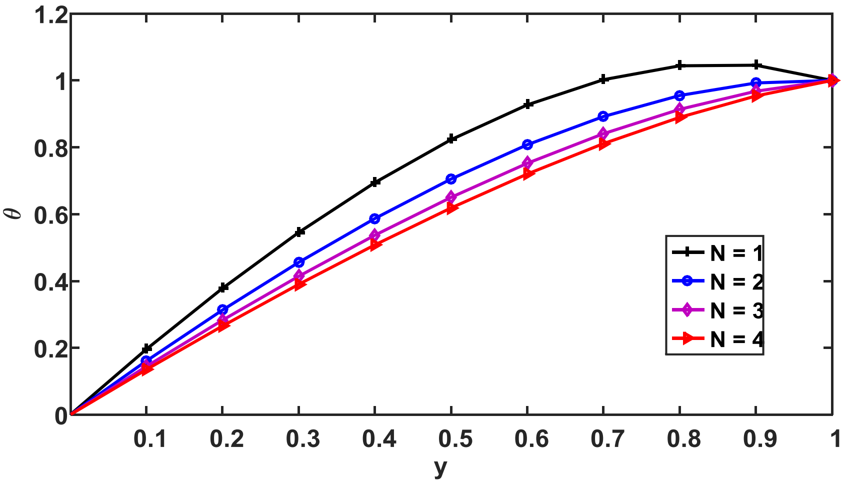

Figure 7: Temperature Profiles For Different *N*When M = 1, *Br*= 10, $\phi = \frac{\pi}{3}$, *A* = 0.01, *Q*= 0.1 And *K* = 0.001

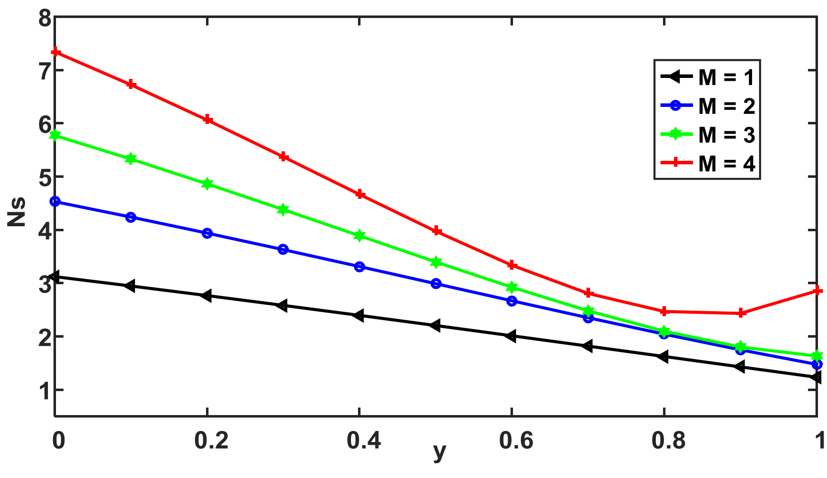

Figure 8: *Ns*For Different M When *A* = 0.01, *Br*= 10, *Q*= 0.1, *N*= 1, *K* = 0.001, ω = 0.4 And $\phi = \frac{\pi}{3}$

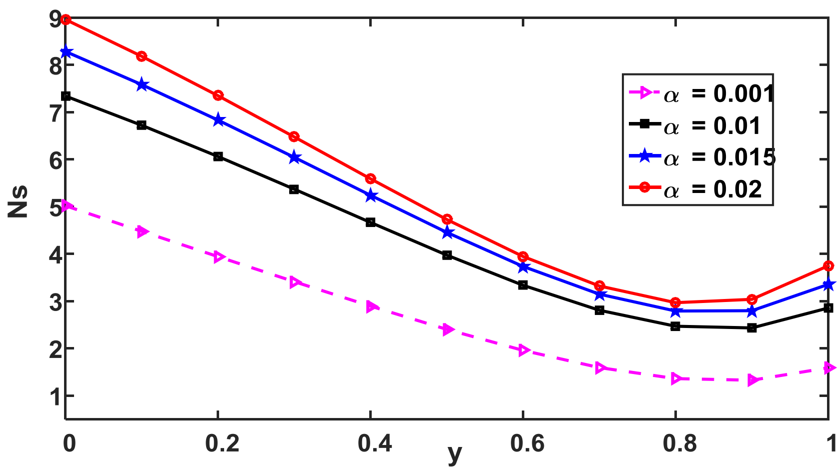

Figure 9: *Ns*For Different *A* When M=1, *Br*= 10, *Q*= 0.1, *N*= 1, *K* = 0.001, ω = 0.4 And $\phi = \frac{\pi}{3}$

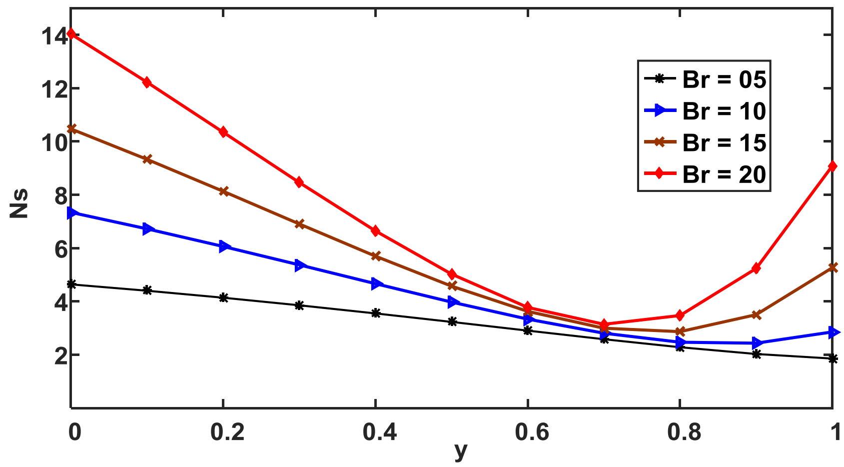

Figure 10: *Ns*For Different *Br*When M=1, *A* = 0.01, *Q*= 0.1, *N*= 1, *K* = 0.001, ω = 0.4 And $\phi = \frac{\pi}{3}$

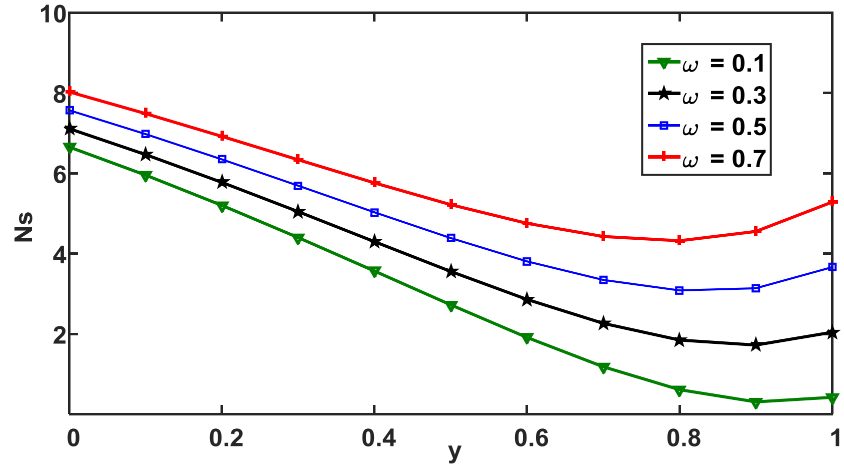

Figure 11: *Ns*For Different ω When M = 1, *A* = 0.01, *Q*= 0.1, *Br* = 10, *K* = 0.001, *N*= 1and $\phi = \frac{\pi}{3}$

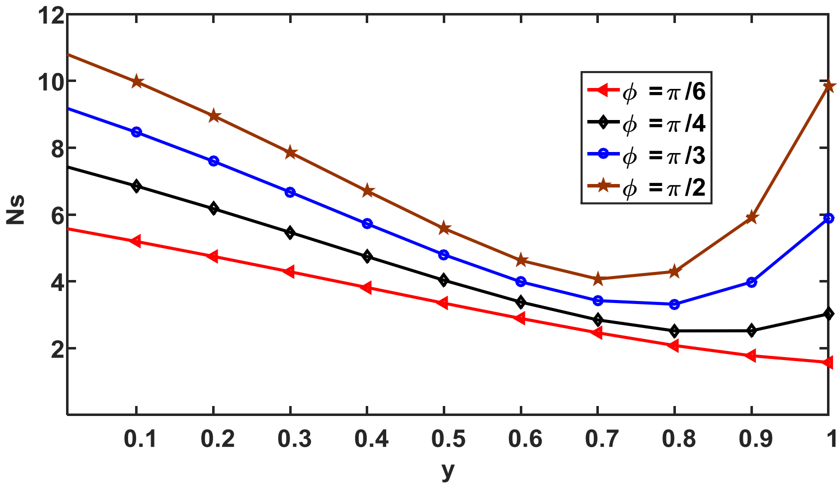

Figure 12: *Ns*For Different ϕ When M= 1, A = 0.01, K = 0.001, Br = 10, ω = 0.4, N= 1 And Q = 0.1

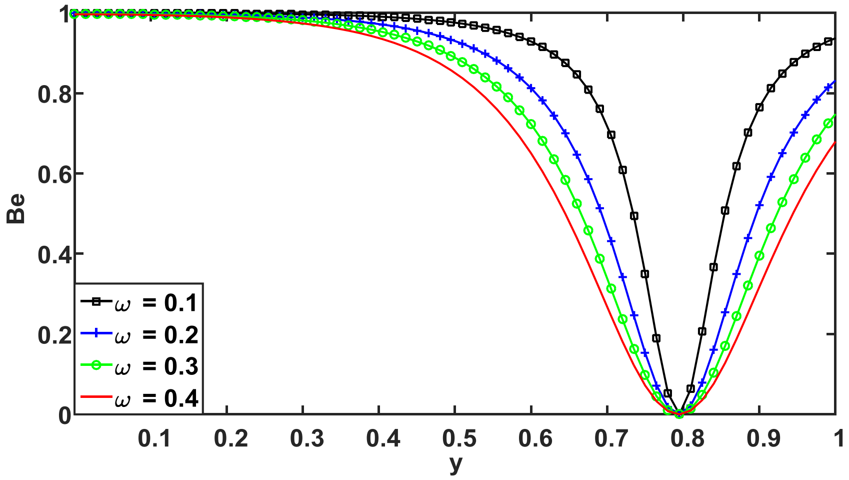

Figure 13: Bejan Number For Different ω When M = 1, A = 0.025, Q= 0.1, Br = 10, K =0.001, N= 1 And

$$\phi = \frac{\pi}{3}$$

Table 1: Numerical Values Of Nusselt Number For Different Values Of Hartmann Number M And Permeability Parameter K With α =0.01, Br =10, N =1, Q =0.1, $\phi = \frac{\pi}{4}$ And $y = 0,1$

$K \backslash M$	$-\theta^1(0)$				$-\theta^1(1)$			
	1	2	3	4	1	2	3	4
0.001	-2.6448	-3.0119	-3.1233	-3.1536	-1.1930	-1.9614	-2.5213	-2.8136
0.002	-2.6554	-3.0185	-3.1257	-3.1543	-1.2856	-2.1070	-.6283	-2.8764
0.003	-2.6617	-3.0218	-3.1268	-3.1546	-1.3404	-2.1832	-2.6817	-2.9068
0.004	-2.6660	-3.0240	-3.1275	-3.1548	-1.3779	-2.2326	-2.7154	-2.9258

Table 2: Skin Friction At The Plates $y = 0$ And $y = 1$

M	*A*	*K*	*Φ*	τ At y = 0	τ At y = 1
1	**0.01**	**0.001**	$\pi/4$	0.1972	0.3999
2	0.01	0.001	$\pi/4$	0.1211	0.4982
3	0.01	0.001	$\pi/4$	0.0653	0.5446
1	**0.02**	0.001	$\pi/4$	0.3248	0.6588
1	**0.03**	0.001	$\pi/4$	0.4142	0.8401
1	0.01	**0.002**	$\pi/4$	0.1487	0.3017
1	0.01	**0.003**	$\pi/4$	0.1252	0.2538
1	0.01	0.001	$\pi/6$	0.2170	0.3578
1	0.01	0.001	$\pi/3$	0.1801	0.4281

VI. Conclusions

Entropy Generation, Heat Transfer, Radiation And Dissipation Effects On A Steady Couette Flow In An Aligned Magnetic Field Bounded Below By A Permeable Bed Have Been Studied And Analyzed. Based On The Results Obtained We Made The Following Conclusions.

- The Fluid Velocity Decreases With Increasing Magnetic Field Parameter M Whereas An Opposite Behavior In Temperature θ Distribution Is Observed.
- The Rising Values Of Brinkman Number Improve The Thermal Boundary Layer Thickness.
- By Increasing Aligned Angle ϕ The Fluid Velocity Decreases And Temperature Increases.
- The Entropy Generation Number Increases With Increasing Values Of M Or α Or Br Or ϕ Or ω.
- Bejan Number Be Decreases With Increasing Values Of ω
- Increasing MOr ϕ Suppresses The Skin Friction At The Wall Y = 0 Whereas It Enhances At The Wall *Y* =1.
- The Friction Factor Coefficient Decreases With Increasing Values Of *K* And An Opposite Trend Is Found With Increasing Values Of α At Both Plates.
- The Heat Transfer Rate Is High At Upper Plate When Compared With Lower Plate.

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