



Entropy generation minimisation in Darcy–Forchheimer flow of a micropolar hybrid nanofluid over a stretching sheet with activation energy and Joule heating

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ABSTRACT

This study investigates the thermodynamic irreversibility of a micropolar hybrid nanofluid (Cu–Al₂O₃/water) over a stretching sheet in a Darcy–Forchheimer porous medium. The objective is to analyse entropy generation minimisation under magnetohydrodynamics (MHD), Joule heating, viscous dissipation and Arrhenius activation energy. The transformed dimensionless ordinary differential equations are solved numerically using the MATLAB bvp4c algorithm and validated against classical analytical solutions. Key quantitative findings indicate that increasing the micropolar vortex viscosity parameter (K from 0 to 1) enhances the skin friction coefficient by 54% while suppressing the local Nusselt number by nearly 78%. Crucially, strong magnetic fields ($M \geq 3.0$) and viscous dissipation trigger a heat transfer reversal ($Nu_x = -1.0213$), directing heat from the fluid into the wall. Thermodynamic analysis reveals that entropy generation is predominantly driven by fluid friction and Joule heating near the boundary, shifting to heat transfer irreversibility in the far-field. Ultimately, these findings provide a critical thermodynamic framework for optimising advanced thermal management systems, polymer extrusion processes and active flow-control devices.

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KEYWORDS

Entropy generation minimisation; micropolar hybrid nanofluid; Darcy–Forchheimer flow; activation energy; Joule heating; numerical simulation

Nomenclature

Symbol Description

Roman letters

a	Stretching rate constant (s^{-1})
$A_1 - A_5$	Dimensionless thermophysical property ratios
B_0	Uniform magnetic field strength (Tesla)
C	Species concentration (mol/m^3)
C_b	Empirical Forchheimer form drag coefficient (Dimensionless)
C_p	Specific heat capacity ($J/kg \cdot K$)
C_w	Concentration at the wall
C_∞	Ambient concentration
D_m	Mass diffusivity (m^2/s)
E_a	Activation energy (J/mol)
$f'(\eta)$	Dimensionless velocity
F	Forchheimer inertial coefficient
$h(\eta)$	Dimensionless micro-rotation
j	Micro-inertia density (m^2)
k	Thermal conductivity ($W/m \cdot K$)
k_r	Chemical reaction rate constant (s^{-1})
K^*	Permeability of the porous medium (m^2)
m	Micro-rotation boundary parameter
n	Fitted rate constant
N	Micro-rotation/Angular velocity (rad/s)
q_w	Surface heat flux (W/m^2)
q_m	Surface mass flux ($kg/m^2 \cdot s$)
Q_0	Volumetric heat generation/absorption coefficient ($W/m^3 \cdot K$)
T	Fluid temperature (K)

T_w	Temperature at the wall (K)
T_∞	Ambient temperature (K)
u, v	Velocity components along x and y directions (m/s)
u_w	Stretching sheet velocity (m/s)
x, y	Cartesian coordinates (m)

Greek symbols

α	Thermal diffusivity (m^2/s)
γ_{hnf}	Spin gradient viscosity ($kg/m \cdot s$)
δ	Temperature difference parameter
η	Dimensionless similarity variable
$\theta(\eta)$	Dimensionless temperature
κ	Vortex viscosity ($kg/m \cdot s$)
κ_B	Boltzmann constant (J/K)
λ	Porosity parameter
μ	Dynamic viscosity ($kg/m \cdot s$)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Dimensionless chemical reaction parameter
σ_{hnf}	Electrical conductivity (S/m)
τ_w	Wall shear stress (N/m^2)
$\phi(\eta)$	Dimensionless concentration
Φ	Nanoparticle volume fraction
ψ	Stream function
Ω	Dimensionless temperature difference parameter

Dimensionless parameters

Be	Bejan number
Br	Brinkman number
C_{fx}	Skin friction coefficient

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