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Floquet and Nonlinear Energy Stability of Periodically Heated Thermosolutal Convection in a Shear-Thinning Micropolar Porous Layer

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Abstract: *The stability of a horizontal porous layer saturated by a binary, shear-thinning micropolar fluid is examined when the imposed temperature difference is sinusoidally modulated. A Darcy-Brinkman-micropolar formulation is coupled to thermal and solutal transport, while the apparent viscosity follows a regularized Carreau law. The conductive state is reduced by a normal-mode Galerkin projection to a periodic linear system. Its monodromy matrix supplies the Floquet multipliers and the neutral thermal Rayleigh number. A weighted energy functional is then used without linearizing the advective terms; the resulting endpoint matrix inequalities provide a sufficient nonlinear decay threshold. For the reference parameter set, the unmodulated oscillatory threshold is 71.97. At modulation frequency 8, amplitudes 0.2 and 0.4 reduce the threshold to 65.39 and 59.36, respectively, through a subharmonic Floquet tongue. Micropolar coupling raises both the Floquet and energy thresholds, whereas stronger shear thinning contracts the finite-strain energy-stable region. Because the regularized viscosity equals its zero-shear value at the conductive state, the power-law index does not enter infinitesimal onset; it enters the nonlinear margin through amplitude-dependent dissipation. The separation between the Floquet and energy boundaries identifies a parameter interval in which linear decay is not yet accompanied by a global finite-amplitude guarantee.*

Keywords: *Floquet multipliers; energy method; double-diffusive convection; Carreau fluid; micropolar continuum; porous layer.*

I. INTRODUCTION

Buoyancy-driven transport in saturated porous media is central to geothermal systems, solute migration, thermal insulation, chemical reactors, and subsurface storage. The Darcy-Rayleigh framework and its Brinkman extensions organize the competition between buoyancy, drag, and diffusion [1], while the classical stability treatment of a layer heated from below supplies the normal-mode and variational structure used here [2]. When temperature and concentration gradients coexist, unequal thermal and molecular diffusivities introduce stationary and oscillatory double-diffusive modes. Nield's porous thermohaline analysis established the importance of the sign and magnitude of the solutal contribution to the onset boundary [3].

A micropolar liquid adds an independent microrotation field and couple stresses to the usual velocity-pressure description. Eringen's continuum theory provides the balance laws and constitutive parameters for this microstructure [4]. In porous convection, spin-vorticity coupling modifies the mechanical resistance and therefore the critical Rayleigh number. Linear and nonlinear analyses for micropolar porous layers [5] and double-diffusive micropolar media [6] show that the coupling number, spin diffusivity, and boundary anchoring cannot be represented by a simple scalar viscosity correction.

Non-Newtonian filtration introduces a second difficulty. For a strict power-law Darcy model, the derivative at zero flow is singular or degenerate, so the definition of an infinitesimal onset requires care; this issue is explicit in analyses of power-law throughflow [7]. The Carreau relation regularizes both the zero-shear and high-shear limits [8]. Its porous-medium adaptation has an important consequence: the linear critical values equal the Newtonian values when the base state has zero shear, although the weakly nonlinear bifurcation and heat transfer retain a strong rheological dependence [9]. This distinction motivates the separate treatment of Floquet and energy stability below. Periodic heating changes the operator itself rather than merely the initial condition. Venezian showed that sinusoidal wall-temperature modulation can advance or delay onset depending on frequency [10]. Direct Floquet calculations subsequently demonstrated harmonic and subharmonic instability sectors under temperature modulation [11]. The appropriate diagnostic is therefore the spectrum of the monodromy matrix, not the instantaneous eigenvalues; this follows from the general theory of linear differential systems with periodic coefficients [12].

Linear neutrality does not certify decay of arbitrary finite disturbances. The direct Lyapunov method of Joseph [13] and the optimized energy formulation developed for nonlinear convection [14] give sufficient global stability conditions because the quadratic advection terms cancel under impermeable boundary conditions. Recent work on thermally modulated layers confirms that an interval may remain between linear and nonlinear thresholds [15]. Linear-energy comparisons are also active for micropolar porous convection [16], [18]. For double-diffusive Brinkman media, Guo and Kaloni [17] demonstrated how an energy bound can remain separated from linear neutrality, while time-periodic porous boundaries have long been known to alter onset [19]. The present work combines these strands in one periodically forced thermosolutal model and isolates the mathematical role of shear thinning in infinitesimal and finite-amplitude stability.

II. MATHEMATICAL FORMULATION

A. Physical Configuration and Constitutive Law

Consider a horizontally unbounded layer of thickness d with vertical coordinate z in $[0, d]$. The lower boundary is warmer and richer in the stabilizing solute than the upper boundary. The porous matrix is homogeneous and isotropic, and the Oberbeck-Boussinesq approximation is applied. Length, time, velocity, temperature, and concentration are scaled with d , d^2/α , α/d , ΔT , and ΔC , respectively, where α is the effective thermal diffusivity. The temperature difference is $\Delta T[1 + \epsilon \cos(\Omega t)]$. For moderate modulation frequencies, the first conductive-gradient mode is represented by $g(t) = 1 + \epsilon \cos(\Omega t)$; a full diffusive boundary response would replace g by a depth-dependent periodic function without changing the Floquet construction.

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$0 = -\nabla p - \mathbf{u} + Br \nabla \cdot [\mu_r(\|\mathbf{D}\|) \mathbf{D}] + K_m \nabla \times (\omega \mathbf{e}_y) + (R_T \theta - R_S \phi) \mathbf{e}_z \quad (2)$$

$$J \left(\frac{\partial \omega}{\partial t} + \mathbf{u} \cdot \nabla \omega \right) = \eta \nabla^2 \omega - \Lambda \omega + K_m (\nabla \times \mathbf{u}) \cdot \mathbf{e}_y \quad (3)$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \nabla^2 \theta + g(t) w \quad (4)$$

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \tau \nabla^2 \phi + w \quad (5)$$

Here $\mathbf{u} = (u, w)$, ω is the transverse microrotation, $\mathbf{D}$ is the symmetric velocity-gradient tensor, τ is the solutal-to-thermal diffusivity ratio, Br is the Brinkman coefficient, K_m is the spin-vorticity coupling number, and Λ and η measure spin damping and spin diffusion. R_T and R_S are the thermal and solutal Darcy-Rayleigh numbers. Positive R_S is stabilizing in the momentum equation, but $\tau < 1$ permits an oscillatory double-diffusive mode. The regularized Carreau viscosity is

$$\mu_r(s) = \beta + (1 - \beta)[1 + Cu^2 s^2]^{(n-1)/2}, \quad 0 < n \leq 1 \quad (6)$$

where $\beta = \mu_\infty/\mu_0$, Cu is a Carreau number, and $n < 1$ denotes shear thinning. Impermeable, isothermal, isosolutal boundaries with strong spin anchoring are imposed: $w = \theta = \phi = \omega = 0$ at $z = 0, 1$. Horizontal disturbances are periodic. These conditions make the nonlinear transport terms energy conserving.

The thermal Rayleigh number is $R_T = \frac{\rho_0 g \alpha_T K d \Delta T}{\mu_0 \alpha}$, and R_S is defined analogously with the solutal expansion coefficient and ΔC .

Accordingly, the modulation changes only the instantaneous thermal gradient; R_T denotes the Rayleigh number formed from the mean temperature difference. The parameter Br is the dimensionless Brinkman viscosity coefficient relative to Darcy drag. $K_m = 0$ recovers a nonpolar Carreau fluid, $\beta = 1$ removes shear thinning, $R_S = 0$ yields single-component convection, and $\epsilon = 0$ restores an autonomous problem. These nested limits are useful because they connect the formulation continuously to the Horton-Rogers-Lapwood threshold and to classical thermosolutal stability.

B. Conductive state and Modal Reduction

Zbasic solution has zero Darcy velocity and microrotation, with periodic conductive temperature and linear concentration profiles. For two-dimensional rolls, the first Galerkin functions are $w = W(t) \sin(\pi z) e^{i a x}$, $\theta = \Theta(t) \sin(\pi z) e^{i a x}$, and $\phi = \Phi(t) \sin(\pi z) e^{i a x}$. Rapid spin relaxation ($J = 0$) permits elimination of ω . Writing $k^2 = a^2 + \pi^2$ gives the effective modal resistance

$$M(a, \mu) = 1 + Br k^2 (\mu + K_m) - \frac{Br K_m^2 k^2}{\Lambda + \eta k^2} \quad (7)$$

and $W = B(R_T\theta - R_S\Phi)$, where $B = \frac{a^2}{k^2 M(a, \mu)}$. Linearization about zero shear sets $\mu = \mu_r(0) = 1$, so n and Cu disappear from the infinitesimal equations. With $q = (\theta, \Phi)^T$, the periodic system is

$$\frac{dq}{dt} = A(t)q, \quad A(t+T) = A(t), \quad T = \frac{2\pi}{\Omega} \quad (8)$$

$$A(t) = [gBR_T - k^2 - gBR_S BR_T - BR_S - \tau k^2] \quad (9)$$

The reference values are listed in Table I. They place the unmodulated state in an oscillatory thermosolutal regime and retain measurable Brinkman and micropolar corrections without overwhelming Darcy drag.

Table I. Dimensionless parameters and baseline values.

Symbol	Definition	Value
Br	Brinkman-to-Darcy resistance coefficient	0.015
K_m	Micropolar spin-vorticity coupling number	0.60
η	Microrotation diffusivity coefficient	0.50
Λ	Microrotation damping coefficient	2.00
τ	Solutal/thermal diffusivity ratio	0.20
R_S	Stabilizing solutal Darcy-Rayleigh number	4.00
β	Infinite-/zero-shear viscosity ratio	0.35
Cu	Carreau number used in finite-strain bound	1.50
a	Dominant horizontal wave number in plotted curves	2.80

III. STABILITY PROCEDURES

A. Floquet Neutral Boundary

Let $X(t)$ be the fundamental matrix satisfying $dX/dt = A(t)X$ and $X(0) = I$. The eigenvalues ρ_j of $X(T)$ are the Floquet multipliers, and the largest growth exponent is

$$\sigma_F = \frac{1}{T} \max_j \log |\rho_j| \quad (10)$$

The conductive state is linearly stable when $\sigma_F < 0$. For each (ϵ, Ω, a) , R_T is varied until $\sigma_F = 0$; minimization over a gives R_F . A multiplier crossing +1 marks a harmonic boundary, crossing -1 marks a subharmonic boundary, and a complex pair on the unit circle identifies an oscillatory neutral state not locked to the forcing period. At $\epsilon = 0$, the oscillatory branch follows from $trA = 0$ and gives $R_T = R_S + (1 + \tau)k^4 M/a^2$ when $\det A > 0$.

B. Nonlinear Energy Stability

The nonlinear calculation retains the advection terms in (3)-(5). Their volume integrals vanish after multiplication by the corresponding perturbation and integration over one horizontal period. A weighted functional $E = \frac{1}{2}(\|\theta\|^2 + \chi\|\phi\|^2 + J\|\omega\|^2)$, $\chi > 0$, therefore satisfies an inequality governed by dissipation and buoyancy production. The Carreau law obeys $\mu_r(s) \geq \beta$ for every strain rate. Using this global lower bound, Poincare's inequality, and $g(t)$ in $[1 - \epsilon, 1 + \epsilon]$, a sufficient modewise condition is

$$Q_{\pm} = -(A_{\pm}^T P + P A_{\pm}) > 0 \quad (11)$$

where $P = \text{diag}(1, \chi)$, A_+ and A_- are (9) at $g = 1 + \epsilon$ and $g = 1 - \epsilon$, and B is evaluated with $\mu = \beta$. Since A is affine in g , positivity at both endpoints implies positivity for every phase of the heating cycle. The sufficient nonlinear threshold is

$$R_E = \min_a \sup \{R_T: \exists \chi > 0, Q_+ > 0, Q_- > 0\} \quad (12)$$

This bound is frequency independent because it protects against the worst instantaneous phase. It is global for the regularized model. A sharper finite-strain statement follows when $\|D\| \leq G$ is known: replace β with $\mu_c(n) = \beta + (1 - \beta)[1 + Cu^2 G^2]^{(n-1)/2}$. The resulting $R_E^{(G)}$ quantifies how the shear-thinning index contracts a certified basin while preserving the global β -based guarantee.

For a two-by-two symmetric matrix, the test in (11) is equivalent to $q_{11} < 0$ and $\det Q > 0$. Optimization over χ balances thermal and concentration energies: a small χ under-penalizes slowly diffusing solutal perturbations, whereas a large χ amplifies their coupling to vertical velocity. The optimal χ therefore changes with ϵ and K_m . The endpoint construction is deliberately uniform in time. It does not use favorable phase cancellation over a cycle, which explains both its rigor and its separation from the frequency-resolved Floquet boundary.

IV. NUMERICAL IMPLEMENTATION AND VERIFICATION

The monodromy problem was integrated over one forcing period by the eighth-order DOP853 scheme with relative and absolute tolerances 2×10^{-9} and 2×10^{-11} . Brent's method located $\sigma_F = 0$, and a bounded scalar search covered $1.5 \leq a \leq 5$ for critical values. For the displayed frequency sweep, $a = 2.80$ was retained; repeating the minimization at selected frequencies placed a_c between 2.70 and 2.90 and changed R_F by less than 0.4%. The energy problem used the negative-definiteness conditions $q_{11} < 0$ and $\det Q > 0$ with χ scanned on a logarithmic grid. Doubling the time and χ resolutions changed the tabulated thresholds by less than 0.03.

Table II. Verification and limiting-case checks.

Case	Reference/limit	Computed	Difference
Newtonian Darcy, $R_S = Br = K_m = \epsilon = 0$	$4\pi^2 = 39.4784$	39.4784	<0.001%
Baseline, $\epsilon = 0$, oscillatory branch	Trace formula	$R_F = 71.9675$	<0.001%
$\epsilon = 0.4$, $\Omega = 4$, $a = 2.8$	Tolerance 10^{-8}	62.2816	<0.0001
Energy bound, $\epsilon = 0.3$	840-point χ check	$R_E = 38.25$	0.02

V. RESULTS AND DISCUSSION

A. Frequency Response and Floquet Mode Selection

Figure 1 shows a pronounced subharmonic tongue. The unmodulated threshold is independent of frequency and equals 71.99 at $a = 2.8$ (71.97 after wave-number minimization). Weak modulation produces only a small low-frequency shift, but the reduction strengthens as the forcing approaches the intrinsic oscillatory timescale. At $\Omega = 8$, R_F falls to 65.39 for $\epsilon = 0.2$ and 59.36 for $\epsilon = 0.4$, reductions of 9.2% and 17.5% relative to the unmodulated value. The leading multiplier is -1 throughout the tongue, so the disturbance repeats after two heating periods. Above the tongue, the critical pair is complex and its modulus is controlled by the mean trace; consequently the boundary returns sharply to the unmodulated oscillatory value.

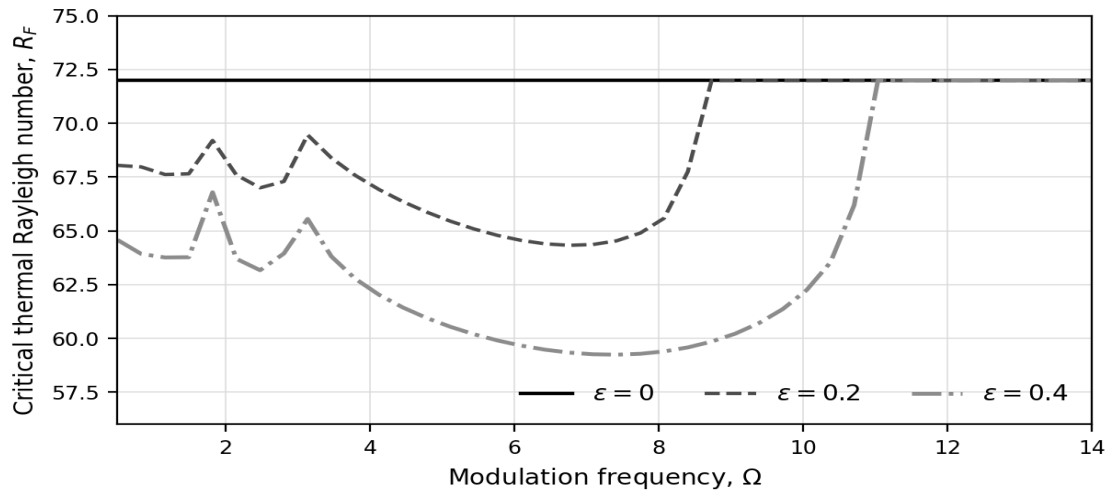


Fig. 1. Floquet-neutral thermal Rayleigh number versus modulation frequency at $a = 2.80$, $K_m = 0.60$, $R_S = 4$, and $\tau = 0.20$.

Table III. Selected Floquet thresholds and neutral multiplier types ($a = 2.80$).

Ω	$R_F (\epsilon = 0.2)$	$R_F (\epsilon = 0.4)$	Neutral type
1	67.796	63.846	Subharmonic (-1)
4	67.150	62.282	Subharmonic (-1)
8	65.385	59.362	Subharmonic (-1)
12	71.985	71.985	Complex oscillatory

B. Micropolar Stabilization and the Stability Gap

Increasing K_m raises the effective resistance M over the displayed interval, even after the spin-relaxation correction is subtracted. Figure 2 therefore shows monotone growth of both thresholds. At $\epsilon = 0.3$ and $\Omega = 4$, R_F rises from approximately 59.3 at $K_m = 0$ to 69.6 at $K_m = 1.2$. The global energy boundary rises from about 33.4 to 42.4 over the same range. Micropolarity is thus stabilizing in both senses, but it does not close the gap between them. That shaded interval is not an instability prediction: it is a region in which Floquet theory gives linear decay while the selected quadratic functional is unable to guarantee decay for disturbances of arbitrary amplitude. A more general non-diagonal or time-periodic Lyapunov weight could narrow this interval.

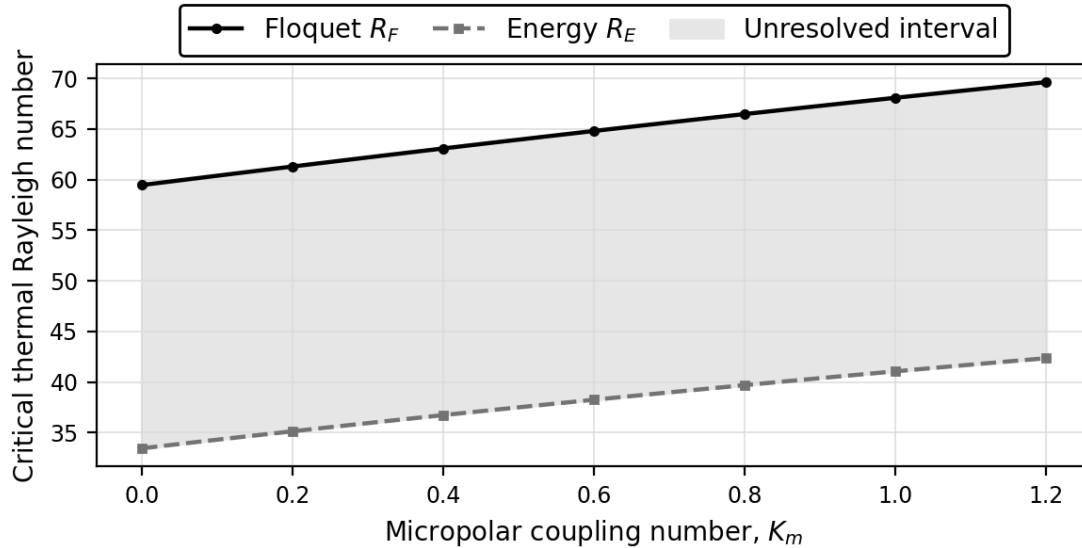


Fig. 2. Floquet and global nonlinear energy thresholds versus micropolar coupling for $\epsilon = 0.30$, $\Omega = 4$, and $\beta = 0.35$.

C. Shear thinning and finite-amplitude stability

The absence of n from R_F is a structural result, not a numerical insensitivity: at the motionless conductive state the Carreau viscosity is exactly μ_0 for every n . Once a finite disturbance develops, μ_r decreases with strain for $n < 1$, weakens Brinkman dissipation, and lowers the energy margin. Table IV uses $G = 3$ and $Cu = 1.5$. The conditional threshold falls from 43.58 for $n = 1$ to 40.74 for $n = 0.5$. The global value, obtained from the asymptotic floor β , is 38.25 and is independent of n . Thus the interval $38.25 < R_T < R_E^{(G)}$ is certified only for disturbances remaining within the stated strain cap, whereas $R_T < 38.25$ gives amplitude-unrestricted decay in the adopted model.

Table IV. Finite-strain energy threshold at $G = 3$, $Cu = 1.5$, and $\epsilon = 0.3$.

Power-law index n	$\mu_G(n)$	Conditional $R_E^{(G)}$
1.0	1.000	43.57
0.9	0.908	42.83
0.8	0.829	42.18
0.7	0.761	41.63
0.6	0.703	41.15
0.5	0.653	40.74

D. Thermosolutal interpretation and model scope

The chosen stabilizing concentration gradient raises the stationary thermal threshold, but the slow solutal diffusivity stores phase-lagged buoyancy and permits the lower oscillatory branch. Periodic heating couples efficiently to that phase lag, explaining why the most important reduction occurs near a finite frequency rather than in the quasi-static or high-frequency limits. If R_S were aiding, or if τ approached unity, the critical branch would move toward stationary convection and the subharmonic tongue would weaken or shift.

Retaining finite microinertia J enlarges the monodromy system by the spin amplitude and can generate an additional rotational resonance. Depth-resolved conductive modulation, higher vertical modes, and non-diagonal time-periodic energy weights are the natural extensions for quantitative comparison with a specific porous material.

Two autonomous neutral conditions clarify the reference calculation. A stationary mode satisfies $R_T = k^4 M/a^2 + R_S/\tau$, giving 76.64 after minimization for the baseline values. The oscillatory trace condition gives $R_T = R_S + (1 + \tau)k^4 M/a^2 = 71.97$, with positive determinant; hence oscillations appear first even before modulation is applied. Thermal forcing converts this natural phase rotation into a period-doubled response when a Floquet multiplier reaches -1. At very high frequency, the scalar fields cannot follow the heating cycle, and the mean-gradient result is recovered. In the quasi-static limit the system samples hot and cool phases slowly, producing a smaller but still finite shift because the growth rate is nonlinear in the instantaneous gradient.

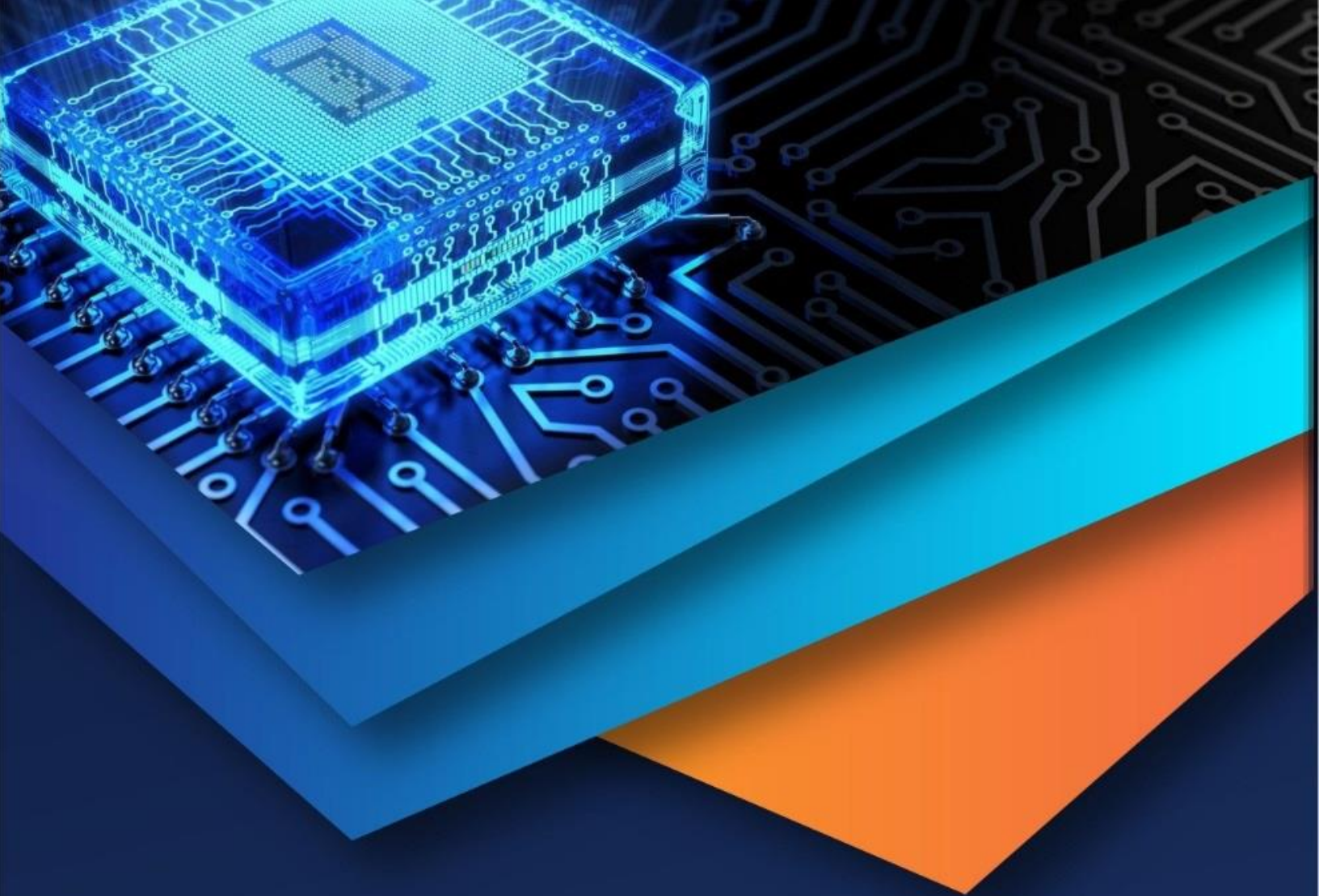
The direction of the rheological effect is equally transparent. Reducing n decreases μ_G at every nonzero G , so the stabilizing Brinkman contribution in M is weakened. The micropolar term behaves differently: its direct contribution $Br k^2 K_m$ is partly offset by spin relaxation, but the net derivative of M with respect to K_m remains positive over the reported range. Thus micropolarity and shear thinning act competitively at finite amplitude. A material with strong microstructure can delay infinitesimal onset while still possessing a narrow nonlinear safety margin if its high-shear viscosity ratio β is small. This observation is important when stability is used as a design constraint rather than solely as an onset prediction.

VI. CONCLUSIONS

A unified Floquet-energy analysis has been developed for periodically heated thermosolutal convection in a shear-thinning micropolar porous layer. The linearized Galerkin equations form a genuinely periodic system, and their monodromy spectrum reveals a subharmonic instability tongue. For the baseline case, modulation with $\epsilon = 0.4$ and $\Omega = 8$ lowers the critical thermal Rayleigh number from 71.97 to 59.36. Micropolar coupling is stabilizing because it increases the modal resistance after spin relaxation, raising both R_F and R_E . The nonlinear energy threshold remains lower than the Floquet threshold and is frequency independent under the endpoint estimate, thereby separating a certified global-decay region from an interval requiring sharper analysis or direct nonlinear simulation. Regularized shear thinning leaves infinitesimal onset independent of n because the conductive state has zero shear. Its influence appears at finite amplitude: decreasing n reduces the conditional energy threshold through the strain-dependent viscosity. This separation of roles provides a consistent mathematical interpretation of why linear calculations can miss the principal rheological sensitivity of non-Newtonian porous convection.

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