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Onset of electrothermoconvection in a dielectric fluid saturated porous medium in a modulated electric field

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Abstract

The onset of electroconvection in a horizontal dielectric fluid saturated with a densely packed porous layer subjected to uniform temperature gradient and an alternating electric field is investigated. The dielectric constant is assumed to be a linear function of temperature. The boundaries are considered to be free-free and isothermal. Modified Darcy equation is used to describe the flow in porous medium and solution to the resulting eigenvalue problem is obtained using a regular perturbation method with small amplitude approximation. The shift in the electric Rayleigh number is calculated as a function of Darcy number, Rayleigh number, frequency of electric modulation and Prandtl number and their effects on the stability of the system are discussed.

Keywords: Electroconvection; modulated electric field; Darcy number; eigen value problem; perturbation procedure.

1. Introduction

Time dependent forces acting on a fluid saturated porous layer can strongly affect instability thresholds and provide an effective way to control convection in various engineering applications. Vibrations, modulations of surface temperature or surface heat flux or alternating electric fields provide examples of periodic forcing on liquids. The effect of time-dependent gravitational or vibration acceleration on the onset of Rayleigh-Benard convection was investigated by many researchers, (see [1]-[4]). On the other hand, the influence of vibration on convection in differentially heated infinite vertical cylinders, in a wide range of frequencies, has been studied by Wadih([5]). Many researchers have studied time periodic modulation of a temperature difference in a liquid layer, (see [6]-[8]) and in porous layer by Rudraiah([9]). The problem of Marangoni instability excited with a time periodic heat flux on the free surface, (see[10]-[12]) and with uniform temperature gradient in the presence of electric field has been carried out. The dynamic excitation of thermoelastic instability in a liquid semiconductor or an ionic melt (see Smorodin[13]) has been investigated. Also, the electrothermoelectric instability of an ohmic non-homogeneous heated liquid subjected to an alternating and modulated electric field Smorodin and Velarde([14]) has been analyzed, when the charge formation is produced by electroconduction.

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In the presence of an electric field, possible convective thresholds in non-uniformly heated liquids actually change due to specific electroconvective instability mechanisms Castellanos([15]) have been carried out. These are dielectrophoresis due to non-homogeneity of the liquid polarization, electroconduction and charge injection. The electrothermal instability of a dielectric liquid subjected to a steady electric field with inhomogeneous polarization has been studied by Turnbull([16]) for the case of a plane horizontal layer. The stability of a plane parallel convective flow in a vertical layer of a dielectric liquid with the boundaries maintained at different temperatures has been investigated by Takashima([17]) in a wide range of Prandtl numbers. Semenov([21]) has studied the parametric excitation instability of a non-uniformly heated dielectric liquid in a horizontal layer, for stress-free boundaries and square wave-form modulation of the electric field. Smorodin and Velarde ([14]) has investigated the convective instability of a liquid dielectric layer with rigid, high electroconductive boundaries subjected to a transverse temperature gradient and on alternating electric field with harmonic modulation. They have considered only the dielectrophoretic mechanism in their stability analyses. This instability mechanism is due to the non-homogeneous dielectric constant of the liquid near the hot and cold electrodes. The conductivity and charge injection have been assumed negligible. The works mentioned above have been concerned with absence of a porous medium. Many practical problems cited above will involve porous layers. Inspite of this much attention has not been given to its study. The study of it is the main objective of this paper. In other words, in the present paper, the electrothermoconvective instability of a dielectric horizontal fluid layer saturated with densely packed porous medium subjected to uniform temperature gradient and an alternating electric field is studied.

2. Mathematical Formulation

We consider a dielectric fluid saturated porous layer confined between two infinite horizontal free surfaces at \( z = -h \) and \( z = h \) constant different temperatures \( T = \pm \Delta T / 2 \) and modulation electric potential of the form \( \varphi = \pm U(\eta_1 + \eta_2 \cos \Omega t) \) are maintained on these boundaries (see fig. 1). Here \( U \) is the amplitude of the potential difference modulation, and \( \Omega \) is its modulation frequency. If the modulation frequency of electric field is below \( 10^9 \text{rad/s} \) and the liquid conductivity is much lower than \( 10^{-7} (\text{m})^{-1} \), then the role of the electric force due to the inhomogeneous dielectric constant will be the major agent in this paper. We assume that the dielectric constant, \( \varepsilon \), of the fluid is a linear function of temperature and the fluid is incompressible and the porous medium is densely packed. For simplicity, we consider the free-free isothermal boundary conditions at the walls.

The basic equations of this configuration along with Boussinesq approximations of an incompressible dielectric fluid in densely packed porous medium are as follows: the conservation of mass, momentum and energy are respectively

\[
\nabla \cdot \vec{q} = 0
\]

\[
\delta \frac{\partial \vec{q}}{\partial t} + \delta^{-2} (\vec{q} \cdot \nabla) \vec{q} = -\nabla P + \frac{\rho}{\rho_0} \vec{g} - \frac{\nu}{K} \vec{q} - \frac{E^2}{2\rho_0} \nabla \varepsilon
\]

\[
A \frac{\partial T}{\partial t} + (\vec{q} \cdot \nabla)T = \chi \nabla^2 T
\]

Where \( P \) is the pressure and \( A \) is specific heat ratio and \( \vec{q} \) is velocity vector. Equation (2) is the modified Lapwood equation (see [18]) and which is modified by means the addition of the last term on the right hand side of equation (2). Following Robert([19]), since the fluid is dielectric, we assume that there are no
free charges. Further there are no induced and applied magnetic fields.

The relevant Maxwell equations are

\[ \nabla \times \overrightarrow{E} = 0 \text{ or } \overrightarrow{E} = -\nabla \varphi \]  
(4)

\[ \nabla (\varepsilon \overrightarrow{E}) = 0 \]  
(5)

\[ \varepsilon = \varepsilon_m (1 + \eta T) \]  
(6)

\[ \rho = \rho_0 (1 - \alpha T) \]  
(7)

Since the basic state is quiescent, the above equations admit an equilibrium solution in which

\[ \overrightarrow{q} = \overrightarrow{q}_b = 0, \quad T = T_b, \quad \overrightarrow{E} = \overrightarrow{E}_b(z,t) \]  
and \( \varepsilon = \varepsilon_b \), where the quantities with suffix \( b \) represent the basic state and they satisfy the equations.

\[ -\nabla P_b + \frac{\rho_b}{\rho_0} \overrightarrow{g} - \frac{E_b^2}{2\rho_0} \nabla \varepsilon_b = 0 \]  
(8)

\[ \frac{d^2 T_b}{dt^2} = 0 \]  
(9)

\[ \nabla (\varepsilon \overrightarrow{E}_b) = 0 \]  
(10)

\[ \varepsilon_b = \varepsilon_m (1 + \eta T_b) \]  
(11)

The solution of equation (9) is given by

\[ T_b = \frac{\Delta T}{2h} (h - 2z) \]  
(12)

Also equation (11) gives

\[ \varepsilon_b \approx \varepsilon_m \left( 1 - \frac{\Delta T h}{h} \right) \]  
and

\[ \frac{d\varepsilon_b}{dz} = -\varepsilon_m \frac{\Delta T}{h} \]  
(13)

Using \( E_b = -\nabla \varphi_b \) in equation (10), the solution for \( \varphi_b \) can be written as

\[ \varphi_b = -\frac{2U(\eta_1 + \eta_2 \cos \Omega t)}{\log(1 - \eta T) h} \log \left( 1 - \eta \frac{\Delta T}{h} \right) + U(\eta_1 + \eta_2 \cos \Omega t) \]  
(14)

Thus we have

\[ E_b = \frac{2U(\eta_1 + \eta_2 \cos \Omega t)}{h} \left( 1 + \eta \frac{\Delta T}{h} \right) \]  
(15)

and

\[ \frac{dE_b}{dz} = \frac{2U(\eta_1 + \eta_2 \cos \Omega t) \eta \Delta T}{h^2} \]  
(16)

To study the stability of the system, we give an infinitesimal disturbance to the basic state so that

\[ \overrightarrow{q} = \overrightarrow{q} + (u', v', w'), \quad P = P_b + P', \quad T = T_b + T', \quad \varepsilon = \varepsilon_b + \varepsilon', \quad \varphi = \varphi_b + \varphi', \quad \overrightarrow{E} = \overrightarrow{E}_b + \overrightarrow{E}', \]  
(17)

where the primes represent the perturbed quantities.

Under the linear approximations and using the basic state equations (8)-(16), equations (1)-(6) reduces to the following linear partial differential equations for the perturbed quantities in equation (17).

\[ \delta^{-1} \frac{d\overrightarrow{q}}{dt} = -\nabla \pi + \alpha g T \overrightarrow{k} - \frac{v}{K} \overrightarrow{q} + B' \overrightarrow{k} \]  
(18)
\begin{equation}
\left( \frac{A}{\partial t} - \chi \nabla^2 \right) T = \frac{\Delta T}{h} w' \tag{19}
\end{equation}

\begin{equation}
\nabla^2 \varphi' = \frac{2U(\eta_1 + \eta_2 \cos \Omega t)}{\varepsilon_m h} \frac{\partial \varepsilon'}{\partial z} - \frac{1}{\varepsilon_m} \frac{d\varepsilon_b}{dz} \frac{\partial \varphi'}{\partial z} \tag{20}
\end{equation}

\begin{equation}
e' = \varepsilon_m \eta T' \tag{21}
\end{equation}

where

\begin{equation}
\pi = P' + \frac{\varepsilon' \varepsilon_0}{\varepsilon_m h} \tag{22}
\end{equation}

and

\begin{equation}
B' = \frac{\Delta T \varepsilon_m \eta}{\rho_0 h} \left( \frac{2U(\eta_1 + \eta_2 \cos \Omega t)}{\varepsilon_m h} e' - \frac{\partial \varphi'}{\partial z} \right) \tag{22}
\end{equation}

Following P.H. Roberts[20], we have used an assumption $\eta \Delta T \ll 1$. Accordingly, we discard any term involving $\eta \Delta T$ compared to a similar term not containing that factor. For example, we neglect the last term in equation (20) in comparison with the term $\nabla^2 \varphi'$ on the left, since their ratio is of order $\eta \Delta T \ll 1$. Under this approximation and using equation (21), equation (20) becomes

\begin{equation}
\nabla^2 \varphi' = \frac{2\eta U(\eta_1 + \eta_2 \cos \Omega t)}{h} \frac{\partial T}{\partial z} \tag{23}
\end{equation}

and equation (23) becomes

\begin{equation}
B' = \frac{2\varepsilon_m \Delta T U(\eta_1 + \eta_2 \cos \Omega t)}{\rho_0 h^2} \left( \frac{2U(\eta_1 + \eta_2 \cos \Omega t)}{h} T' - \frac{\partial \varphi'}{\partial z} \right) \tag{24}
\end{equation}

It follows that

\begin{equation}
\nabla^2 B' = \frac{4\eta^2 \varepsilon_m \Delta T U^2(\eta_1 + \eta_2 \cos \Omega t)}{\rho_0 h^3} \nabla^2_H T' \tag{25}
\end{equation}

To eliminate the pressure from equation (18), we operate curl twice on it, which yields an equation of the form

\begin{equation}
\left( \frac{1}{\partial t} + \frac{\nu}{K} \right) \nabla^2 w' = a g \nabla^2_T T' + \nabla^2_H B' \tag{26}
\end{equation}

Since the walls are stress free and isothermal, the boundary conditions are given by

\begin{equation}
w' = \frac{\partial^2 w}{\partial z^2} = T' = \varphi' = 0 \text{ at } z = 0, h \tag{27}
\end{equation}

Using equations (20) and (23) in equation (25), we obtain the following equation

\begin{equation}
\left[ \frac{h}{\Delta T} \left( \frac{1}{\partial t} + \frac{\nu}{K} \right) \left( A \frac{\partial}{\partial t} - \chi \nabla^2 \right) - a_g \nabla^2_H \right] = \frac{4\eta^2 \varepsilon_m \Delta T U^2(1 + \eta_3 \cos \Omega t)^2}{\rho_0 h^3} \nabla^2_H T' \tag{28}
\end{equation}

where $\eta_3 = \frac{\eta_2}{\eta_1}$ is the ratio of modulation amplitude to steady amplitude of the electric potential.

Equation (28) is made dimensionless using the transformations $(x', y', z') = \frac{1}{h}(x, y, z), T^* = \frac{T}{T_p}, t^* = \frac{t}{T_p}$ and $\omega = \frac{\Omega x}{h}$ and hence obtain (after dropping asterisks)

\begin{equation}
\left[ \left( \frac{1}{A \delta P_r} \frac{\partial}{\partial t} + \frac{1}{D_x} \left( \frac{\partial}{\partial t} - \nabla^2 \right) \right) - R_a \nabla_H^2 \left( \nabla^2 T' = R_e(1 + \eta_3 \cos \Omega t)^2 \nabla^4_H T' \right) \tag{29}
\end{equation}

where $R_a = \frac{a \Delta T h^3}{v_x}, R_e = \frac{4\eta^2 U^2 \varepsilon_m \eta_1^2 \Delta T^2}{\rho_0 v_x}$ and $P_r = \frac{\nu}{h}$ are respectively Rayleigh number, Electric Rayleigh number and Prandtl number.

The boundary conditions (27) involve $w'$ and $\varphi'$ in addition to $T'$. These $w'$ and $\varphi'$ can also be expressed in terms of
$T'$ by making use of equations (20), (24) and (25), which requires $\frac{\partial T'}{\partial z} = 0$ if $w'$, $\varphi'$ and $T'$ are zero. Thus equation (29) has to be solved subject to the dimensionless homogeneous boundary conditions

$$T' = \frac{\partial^2 T'}{\partial z^2} = \frac{\partial^4 T'}{\partial z^4} = 0 \text{ at } z = 0, 1$$

(30)

We look for solution of $T'$ in the form $T' = T(z, t)e^{i(k_1x + k_2y)}$ and hence obtain $\nabla^2 T' = -k^2 T'$, where $k^2 = k^2_1 + k^2_2$. Then equations (28) and (29) respectively become

$$\left[ \left( \frac{1}{A_0 \rho F} \frac{\partial}{\partial t} + \frac{1}{D_0} \right) \left( \frac{\partial}{\partial t} - (D^2 - k^2) \right) (D^2 - k^2)^2 + k^2 R_0 (D^2 - k^2) \right] T = R_e k^4 (1 + \eta_3 \cos \omega t)^2 T$$

(31)

$$T' = \frac{\partial^2 T'}{\partial z^2} = \frac{\partial^4 T'}{\partial z^4} = 0 \text{ at } z = 0, 1$$

(32)

This is an eigenvalue problem for an eigenvalue $R_e$. To obtain an expression for the eigenvalue $R_e$ of (31).

3. Perturbation Procedure With Small Amplitude Approximation

In the present study the eigen functions and eigen values differ from those associated with unmodulated system by the quantities of order $\eta_3$. Where $\eta_3$ is assumed to be small compared to unity. We therefore assume the solution in the form

$$T = T_0 + \eta_3 T_1 + \eta_3^2 T_2 + \ldots \text{ and } R_e = R_{eo} + \eta_3 R_{e1} + \eta_3^2 R_{e2} + \ldots$$

(33)

Substituting equation (32) into equation(31) and equating the coefficients of like powers of $\eta_3$, we obtain the following system of equations

$$LT_0 = 0$$

(34)

$$LT_1 = 2R_{eo} k^4 \cos \omega T_0 + R_{e1} k^4 T_0$$

(35)

$$LT_2 = R_{eo} k^4 \cos \omega^2 T_0 + 2R_{e0} k^4 \cos \omega T_1 + R_{e2} k^4 T_0$$

(36)

Where $L = \left( \frac{1}{A_0 \rho F} \frac{\partial}{\partial t} + \frac{1}{D_0} \right) \left( \frac{\partial}{\partial t} - (D^2 - k^2) \right) (D^2 - k^2)^2 + k^2 R_0 (D^2 - k^2) \right]$. 

Now using (30) in (35), it is clear that each $T_0$, $T_1$, $T_2$ should satisfy the boundary conditions (33) and equation (33) is the one used in the study of convection in a horizontal dielectric fluid saturated porous layer subject to uniform electric field and marginally stable solutions should be

$$T^{(n)}_0 = \sin n\pi z$$

(37)

The corresponding eigenvalues are given by

$$R_{eo}^{(n)} = \frac{(n^2 \pi^2 + k^2)^3}{D_0 k^4} - \frac{R_0 (n^2 \pi^2 + k^2)}{k^2}$$

(38)

The least eigenvalue occurs for the mode $n = 1$ for fixed wave number $k$ and hence the least eigenvalue is given by

$$R_{eo} = \frac{(\pi^2 + k^2)^3}{D_0 k^4} - \frac{R_0 (\pi^2 + k^2)}{k^2}$$

(39)

corresponding to an eigen function $T_0 = \sin \pi z$. $R_{eo}$ assumes the minimum value $R_{ec}$ for $k = k_c$, where $k_c$, obtained from $\frac{\partial R_{ec}}{\partial k_c} = 0$, satisfies the equation

$$(k_c^2)^3 - \pi^2 (3\pi^2 - R_0 D_0) k_c^2 - 2\pi^6 = 0$$

(40)

The solubility condition requires that the time-independent part of the right hand side of the equation (34) should be orthogonal to $\sin \pi z$. Since the first term in right hand side of equation (34) varies sinusoidaly in time, the only steady
term is \( R_{e1}k^4T_0 \), so that \( R_{e1} \) is zero. It can be shown that the all odd coefficients i.e., \( R_{e3}, R_{e5} \),... in equation (32) are zero. Equation (34) for \( T_1 \) now takes the form

\[
LT_1 = 2R_{eo}k^4 \cos \omega t \sin \pi z
\]

\[
L(\omega, n) = \left( -\frac{\omega^2 \tau^2}{A\delta P_r} + \frac{\tau^4}{D_a} - R_{eo}k^2 \tau - R_{eo}k^4 \right) - i \left( \frac{\tau^3}{A\delta P_r} + \frac{\tau^2}{D_a} \right) \]

where \( \tau = (n^2 \pi^2 + k^2) \). It follows that \( L \sin n \pi z e^{-i\omega t} = L(\omega, n) \sin n \pi z e^{-i\omega t} \). Now from equation (40), we have

\[
T_1 = 2R_{eo}k^4 \Re \left( \frac{\sin n \pi z}{L(\omega, n)} e^{-i\omega t} \right)
\]

Equation for \( T_2 \) then reads

\[
LT_2 = R_{eo}k^4 \cos \omega T_0 + 2R_{eo}k^4 \cos \omega T_1 + R_{e2}k^4 T_0
\]

Since we are interested in determining the value of \( R_{e2} \), the first non-zero correction to \( R_e \), there is no need to solve for \( T_0 \). However, \( T_2 \) can also be solved in the same manner after the determination of \( R_{e2} \). The solubility condition requires that the steady part of the right hand side should be orthogonal to \( \sin \pi z \) and this results the following equation:

\[
R_{e2} = -R_{eo} \left( \cos^2 \omega t \right) + 4 \int_0^1 \Re \left( \frac{1}{T_1} \cos \omega t \sin \pi zdz \right)
\]

Here bar denotes a time average of the quantities. Using equations (40) and (42) in the equation (44), we obtain

\[
R_{e2} = -R_{eo} \left( \frac{1}{2} + R_{eo}k^4 \frac{L(\omega, n) + L'(\omega, n))}{|L(\omega, n)|^2} \right)
\]

where the superscript * denotes the complex conjugate. The critical value of the electric Rayleigh number \( R_e \) is computed up to \( O(\eta_k^3) \) by evaluating \( R_{eo} \) and \( R_{e2} \) at \( k = k_c \) for fixed values of \( R_a, D_a \) and \( P_r \). The results are depicted in Figs. 2-4.

4. Results and Conclusions

In this section, we discuss the effect of electric modulation, Darcy number and Prandtl number on the onset of electrothermoconvection in a horizontal dielectric fluid saturated porous layer using linear stability analysis. In the present paper, the eigenvalue \( R_e \) is obtained in terms of power series in \( \eta_k \), the ratio of amplitudes of the modulated and steady electric potentials and is determined to the order of \( \eta_k^3 \). Accordingly we have \( R_e = R_{eo} + \eta_k^2 R_{e2} \). Here we note that \( R_{e1} \) is zero as shown in section 3. \( R_{eo} \) and \( R_{e2} \) are, respectively, given by equations (38) and (46) and evaluated at \( k = k_c \). \( R_{eo} \) is the electric Rayleigh number for the convection problem in a dielectric fluid saturated porous layer in the absence of electric modulation and \( R_{e2} \) is the first nonzero correction to \( R_e \). If \( R_{e2} \) is positive, then the value of total \( R_e \) is greater than the value of electric Rayleigh number for the case of convection without modulation. In this case we say that the system is more stable. In a similar way, if \( R_{e2} \) is negative, we say that the system is more unstable. Without modulation, which corresponds to steady onset, the critical electric Rayleigh number \( R_{eo} \) depends on the Darcy number \( D_a \) and thermal Rayleigh number \( R_a \) and is independent of the Prandtl number \( P_r \). However, the shift in electric Rayleigh number \( R_{e2} \) can be altered by \( P_r \) when the electric modulation is taken into account.

The correction electric Rayleigh number \( R_{e2} \) is obtained as a function of Rayleigh number \( R_a \), frequency of electric modulation \( \omega \), Darcy number \( D_a \) and Prandtl number \( P_r \) and is depicted in figures 2-4.

Figure 2 shows the variation of correction electric Rayleigh number \( R_{e2} \) with frequency of modulation \( \omega \) for different values of \( \pm R_a \) and for fixed values of \( D_a = 10^{-3}, P_r = 0.01 \). From this figure we observe that for small \( \omega \), \( R_{e2} \) is positive, indicating that the effect of electric modulation is to stabilize the system. For moderate and large values of \( \omega \) the correction electric Rayleigh number \( R_{e2} \) is negative, indicating that the electric modulation has a destabilizing effect for moderate and large values of the frequency. Further, at some particular value of the frequency \( \omega \) the effect of modulation ceases i.e., \( R_{e2} = 0 \). Also, it is important to note from this figure that, when \( R_a \) is positive (heating from
below) instability occurs earlier than when \( R_a \) is negative (heating from above). We also observe from this figure that for a given value of \( \omega \), \( R_{e2} \) increases with increasing Rayleigh number \( R_a \) indicating that the growth of the Rayleigh number leads to an increase of the stability thresholds.

Figure 3 displays the variation of correction electric Rayleigh number \( R_{e2} \) with \( \omega \) for different values of \( D_a \) and for fixed values of \( P_r = 0.01 \), \( R_a = 10^4 \) and \( R_a = -10^4 \). We find that for small value of \( \omega \), as \( D_a \) increases, \( R_{e2} \) decreases whereas \( R_{e2} \) increases as \( D_a \) increases for moderate and large values of \( \omega \), indicating that the effect of \( D_a \) is to destabilize the system for lower values of frequency and is to stabilize the system for moderate and higher values of frequencies. Further, at some value of \( \omega \), the effect of \( D_a \) ceases as \( R_{e2} \rightarrow 0 \). From this figure, we also observe that negative \( R_a \) is more effective than the positive \( R_a \). That is, the system is more stable when it is heated from above than heating from below.

Figure 4 shows the variation of electric Rayleigh number \( R_{e2} \) with \( \omega \) for different values of \( P_r \) and for fixed values of \( D_a = 10^{-3} \), \( R_a = 10^4 \) and \( R_a = -10^4 \). This figure indicates that as \( P_r \) increases, \( R_{e2} \) increases for both positive \( R_e \) and negative \( R_e \), indicating that the effect of \( P_r \) is to suppress the onset of convection. The \( R_a \) in figure also indicates that the effect of \( P_r \) on the onset of convection ceases for some value of \( \omega \), for which \( R_{e2} \rightarrow 0 \). Further we observe that negative \( R_a \) is more effective than the positive \( R_a \).

The combined effect of electric modulation and uniform temperature gradient on the onset of electrothermoconvecive instability in a horizontal dielectric fluid saturated porous layer is studied in this paper using linear stability analysis based on the assumption that the amplitude of the modulating electric potential is small compared with the imposed steady electric potential. The effect of modulated electric field is to stabilize the system for small values of the frequency \( \omega \) and it has a destabilizing effect for moderate and large values of \( \omega \), whereas the effect of \( D_a \) is to oppose
the effect of electric Rayleigh number $R_e$. The effect of $P_r$ is to suppress the onset of convection. Further we conclude that the system is more stable when it is heated from above than below.

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