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Stabilising solar ponds by utilising porous materials

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ABSTRACT

The linear instability of a solar pond containing porous material in the lower convective zone (LCZ) is investigated. It is found that, in general, for physically realistic values, solar ponds that contain porous material are more stable than ones that do not. Interestingly, it is found that the percentage of porous material contained in the LCZ does not stabilise the system in a linear fashion and, in particular, approximately 60% of porous material in the LCZ appears to optimise the maximum temperature that can be stored in the LCZ provided the proportion of heat flux extracted at the base of the pond, f, is held fixed at a physically realistic value of $f = 0.5$. When f is varied it is found that there is a critical value of $f = 0.6$ below which inclusion of porous material stabilises the system but above which it does not.

1. Introduction

Salt gradient solar ponds (which will be referred to as solar ponds) are pools of saltwater which can collect and store solar thermal energy. They consist of three well-defined layers, namely, an upper convective zone (UCZ), a lower convective zone (LCZ) and a non-convective gradient zone (NCZ), that separates the UCZ and the LCZ, see Fig. 1. The salinity and temperature in the convective zones are considered to be uniform while both the salinity and temperature in the NCZ increase linearly with depth. The temperature within a solar pond typically ranges from 20 °C at the top to 90 °C at the bottom while the salinity varies from a low value at the surface to a value close to saturation in the LCZ [1,2]. The NCZ works as an insulator to limit double-diffusion of heat and salt from the LCZ to the UCZ while the LCZ acts as a collection and storage area.

Solar ponds have been extensively studied (see [3–7] and references therein) and are considered to be a reliable and economical source for long-term heat collection and storage [8]. While the majority of studies have focussed on solar ponds made only of fluid, more recent studies [9–12] have considered the introduction of porous media at the base of the pond. The porous media has been shown to effect (i) the stability of the pond and (ii) heat loss at the base of the pond. This in turn has important consequences for the efficiency of the pond.

When a solar pond is heated by the absorption of solar radiation, the radiation must pass through the UCZ and NCZ if it is to reach the LCZ and provide useful heat. Once absorbed in the LCZ the heat is trapped provided the concentration gradient in the NCZ is great enough to prevent convective motion. Inevitably when the temperature in the LCZ reaches a critical value convective motion will occur and lead to the destruction of the interface between the LCZ and the NCZ (and ultimately the structure of the pond itself). Hence understanding the stability of a pond is integral in assessing its efficiency. Investigating heat loss at the bottom of a solar pond, is also crucial since heat loss at the base is known to be proportional to ground thermal conductivity [13] and to have an influence on the thermal efficiency of a solar pond [14].

Al-Juwayhel & El-Refaee [9] were first to perform numerical simulations which calculated the thermal conductivity of a mixture of brine and porous media in the context of a solar pond. They found that inserting a rock bed at the bottom of a solar pond generally enhanced the temperature of the LCZ. Shi et al. [12] did an in depth experimental and numerical study of the effects of a porous media on the thermal and salt diffusion properties of a solar pond. Their experimental results also showed that the addition of porous media to the bottom of a solar pond could increase the temperature in the LCZ. Moreover, they found that the presence of a porous media slowed down the upward diffusion of salt and so helped to maintain the NCZ. However, their numerical simulations showed that while the addition of a porous media had a positive effect on insulating the base when the thermal conductivity of the ground was large it may have an adverse effect when the thermal conductivity was very small. Karim et al. [11] performed small-scale laboratory experiments and middle-scale outdoor experiments to study the stability of a solar pond. Like Shi et al. [12] they too found that the introduction of a porous bed could stabilise the system.

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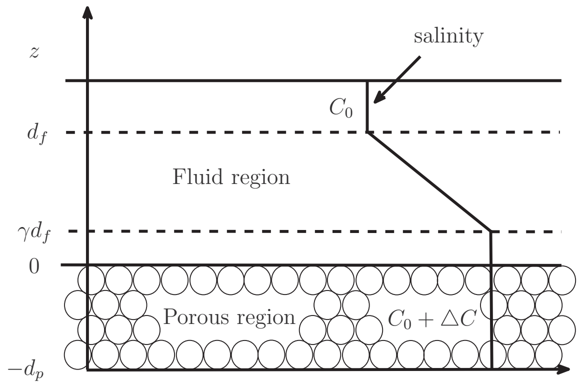

Fig. 1. Schematic representation of the structure of a solar pond, with a fluid-porous interface within the lower convective zone (LCZ).

General discussions on fluid-porous interface modelling may be found in [15–18].

In this paper a solar pond with and without porous material situated in the LCZ is considered. A linear instability analysis is performed and it is shown that in general, for physically realistic values, the introduction of the porous material stabilises the system. However, when the proportion of heat flux extracted from the LCZ, f, is varied it is found that there is a critical value of $f = 0.6$ below which inclusion of porous material stabilises the system but above which it does not. The percentage of porous material contained within the LCZ is varied and it is found that 60% optimises the temperature that can be attained in the LCZ, for a physcially realistic value of $f = 0.5$.

2. Formation of the problem

Let us consider a fluid occupying the three-dimensional layer $\{(x,y) \in \mathbb{R}^2\} \times \{z \in (0, d_f)\}$, overlying a homogeneous porous medium occupying the layer $\{(x,y) \in \mathbb{R}^2\} \times \{z \in (-d_p, 0)\}$. The interface between the saturated porous medium and the fluid layer is at $z = 0$ (see Fig. 1).

To emulate the structure of a solar pond, the upper convective zone (UCZ) is situated above the plane $z = d_f$, the gradient zone (NCZ) is contained between the planes $z = \gamma d_f \ \ (\gamma \in (0,1))$ and $z = d_f$, and the lower convective zone (LCZ) is contained between the planes $z = -d_p$ and $z = \gamma d_f$. The concentration is taken to be C_0 in the UCZ and $C_0 + \triangle C$ in the LCZ (see Fig. 1).

Under this configuration the porous material forms part of the LCZ as required.

Gravity acts in the negative z-direction, and we assume that the density ρ in the fluid region has a linear temperature and salinity dependence of the form

$$\rho(T^\tau, C^\tau) = \rho_0(1 - \alpha_t(T^\tau - T_0) + \alpha_c(C^\tau - C_0)),$$

where T^τ is the temperature, C^τ is concentration and ρ_0, T_0 and C_0 are the reference density, temperature and concentration values, respectively. α_t and α_c are the coefficients of thermal and solutal expansion. The implementation of a linear density approximation is justified over a specific range of temperature and concentration values (which vary with season and local forcing) [1,19], under which this study is conducted.

The superscript τ defines which distinct region within the fluid layer the governing equations describe, with $\tau = \mathrm{NCZ}$ for the gradient zone and $\tau = \mathrm{LCZ}$ for the lower convective zone.

Utilising Lambert's law, the rate of energy generation per unit volume in the fluid layer due to the absorption of solar energy is given by

$$\dot{q} = q(d_f)\beta_f e^{\beta_f(z-d_f)} \quad \text{for} \quad z \in [0, d_f],$$

where $q(d_f)$ is the heat flux due to solar radiation at the upper boundary of the fluid layer. The transparency of the fluid medium is described through the extinction coefficient β_f [4,5].

The governing equations in the fluid region are given by the Navier-Stokes flow equations

$$\rho_0\left(\frac{\partial \mathbf{v}^\tau}{\partial t} + (\mathbf{v}^\tau \cdot \nabla)\mathbf{v}^\tau\right) = -\nabla p^\tau + \mu\nabla^2\mathbf{v}^\tau - \mathbf{k}g\rho(T^\tau, C^\tau) \tag{1}$$

$$\nabla \cdot \mathbf{v}^\tau = 0, \tag{2}$$

$$\frac{\partial T^\tau}{\partial t} + \mathbf{v}^\tau \cdot \nabla T^\tau = \kappa_f \nabla^2 T^\tau + \frac{\dot{q}}{(\rho_0 c_p)_f}, \tag{3}$$

$$\frac{\partial C^\tau}{\partial t} + \mathbf{v}^\tau \cdot \nabla C^\tau = \kappa_c \nabla^2 C^\tau, \tag{4}$$

where (2)–(4) are the incompressibility condition, balance of energy, and balance of solute, respectively.

In these equations $\mathbf{v}^\tau = (u^\tau, v^\tau, w^\tau), p^\tau, t$ and μ are velocity, pressure, time and dynamic viscosity respectively. κ'_f, κ_c, g and c_p are the thermal diffusivity, solutal diffusivity, acceleration due to gravity and specific heat at a constant pressure respectively, with $\kappa_f = \kappa'_f/(\rho_0 c_p)_f$. The remaining parameter is the vector $\mathbf{k} = (0,0,1)$.

Following the same linear density approximation employed for (1), the governing equations in the porous region are given by Darcy's flow equation (as we are considering a quiescent base state, and materials that do not have porosity greater than 0.7, see [20])

$$\frac{\mu}{K}\mathbf{v}^P = -\nabla p^P - \mathbf{k}g\rho(T^P, C^P), \tag{5}$$

$$\nabla \cdot \mathbf{v}^P = 0, \tag{6}$$

$$\frac{(\rho_0 c_p)_p}{(\rho_0 c_p)_f}\frac{\partial T^P}{\partial t} + \mathbf{v}^P \cdot \nabla T^P = \kappa_p \nabla^2 T^P + \frac{\dot{q}}{(\rho_0 c_p)_f}, \tag{7}$$

$$\varepsilon\frac{\partial C^P}{\partial t} + \mathbf{v}^P \cdot \nabla C^P = \varepsilon\kappa_c \nabla^2 C^P, \tag{8}$$

where (6)–(8) are the incompressibility condition, balance of energy, and balance of solute, respectively.

The P superscript refers to the porous medium, with those parameters having the same definitions as for (1)–(4). K and ε are the permeability and porosity of the porous medium, respectively, and $\kappa_p = \kappa'_p/(\rho_0 c_p)_f$. For $Q_p = \kappa'_p$ or $(\rho_0 c_p)_p$, the remaining parameters are defined in terms of the fluid (f) and solid (s) components of the porous medium, such that $Q_p = \varepsilon Q_f + (1-\varepsilon)Q_s$.

The rate of energy generation per unit volume in the porous layer due to the absorption of solar energy is given by

$$\dot{q} = q(d_f)\beta_p e^{\beta_p z - \beta_f d_f} \quad \text{for} \quad z \in [-d_p, 0],$$

where β_p is the porous layer extinction coefficient.

At the interface between the NCZ and LCZ fluid layers at $z = \gamma d_f$, the continuity of velocity, normal and tangential stresses (cf., [21–23]), temperature, concentration, heat flux and solute flux respectively yield

$$\begin{aligned}
&\mathbf{v}^{\mathrm{NCZ}} = \mathbf{v}^{\mathrm{LCZ}}, \quad -p^{\mathrm{NCZ}} + 2\mu\frac{\partial w^{\mathrm{NCZ}}}{\partial z} = -p^{\mathrm{LCZ}} + 2\mu\frac{\partial w^{\mathrm{LCZ}}}{\partial z},\\
&\mu\left(\frac{\partial u^{\mathrm{NCZ}}}{\partial z} + \frac{\partial w^{\mathrm{NCZ}}}{\partial x}\right) = \mu\left(\frac{\partial u^{\mathrm{LCZ}}}{\partial z} + \frac{\partial w^{\mathrm{LCZ}}}{\partial x}\right),\\
&\mu\left(\frac{\partial v^{\mathrm{NCZ}}}{\partial z} + \frac{\partial v^{\mathrm{NCZ}}}{\partial y}\right) = \mu\left(\frac{\partial v^{\mathrm{LCZ}}}{\partial z} + \frac{\partial w^{\mathrm{LCZ}}}{\partial y}\right), \quad T^{\mathrm{NCZ}} = T^{\mathrm{LCZ}},\\
&C^{\mathrm{NCZ}} = C^{\mathrm{LCZ}}, \quad \kappa'_f\frac{\partial T^{\mathrm{NCZ}}}{\partial z} = \kappa'_f\frac{\partial T^{\mathrm{LCZ}}}{\partial z}, \quad \kappa_c\frac{\partial C^{\mathrm{NCZ}}}{\partial z} = \kappa_c\frac{\partial C^{\mathrm{LCZ}}}{\partial z}.
\end{aligned} \tag{9}$$