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A laboratory experimental study of mixing the solar pond gradient zone

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Abstract

The efficiency and the lifetime of a solar pond depends mainly on the behavior of the gradient Non-Convective Zone (NCZ), embedded between an Upper Convective Zone (UCZ) and a Lower Convective Zone (LCZ).

The NCZ is often the siege of instabilities. These instabilities can destroy the linearity and transform it to a well mixed layer leading the pond to loose its main role of storing.

Series of laboratory studies have been carried out to assess the stability of a linearly salt-stratified system (simulating the NCZ of a solar pond) heated from below. An assortment of flow visualization by Shadowgraph and Particle Image Velocimetry (P.I.V) techniques was employed to provide a phenomenological description of flow convection.

This experimental characterization reveals three specific stages. The first stage corresponds to the onset of a non periodic oscillation in space and time of the bottom flow. In a second stage a well mixed layer is born and an oscillatory movement appears at the free surface whereas the last stage is relative to the transition from linear stratification to non-linear one (two superimposed layers separated by a well thin interface), *before the homogenization of the whole system is accomplished.*

Most theoretical and experimental studies in the literature, considered a gradient layer heated from below at constant heat flux, whereas in this work the free surface system is heated from below at constant temperature. In addition, we will focus on the onset and development of the first mixed layer for small values of stability parameter Λ (values that can be encountered in a real solar pond. In the vicinity of our laboratory a 3 m-deep solar pond of 1500 m^2 area is available). To our knowledge, no investigations has been performed, on the birth and self-organization of the first layer for small values of Λ.

Keywords: Solar pond; Gradient zone (NCZ); Double-diffusion; P.I.V b; Shadowgraph

1. Introduction

The salt stratified solution, destabilized by bottom heating, is a double-diffusive system (Turner, 1979). This system can be encountered in many industrial and engineering applications, such as the salt gradient solar pond (Zangrando, 1991), the thermohaline structure of the upper ocean, the storage of liquefied gas and mantle convection (Kantha, 1980).

The solar pond is a reservoir of salt water used to collect and store solar radiations around the year. Its concentration increases with depth, going from a rather low value on the surface to a value close to saturation in bottom. The depth varies, but is 3–4 m on the average, and 1.5 m of that are reserved to the saline gradient zone. In fact, a solar pond consists of three layers of water with a different saline gradient as shown in Fig. 1: the Lower Convective Zone (LCZ), the Non-Convective Zone (NCZ) and the Upper Convective Zone. The NCZ acts as an insulator against heat and mass diffusion. The UCZ is a thin layer used to bear all the environmental influences.

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Nomenclature

A	aspect ratio
$\overline{C}$	constant
a	constant
C	concentration (%)
C_p	specific heat (J/kg °C) – *uncertainty* ± 0.2%
g	gravitational acceleration (m/s^2)
H	stratified layer height (m)
h	height of the first mixed layer (m)
κ_T	coefficient of thermal diffusion (m^2/s)
κ_S	coefficient of solute diffusion (m^2/s) – *uncertainty* ± 5%
Q	bottom heat flux (W/m^2)
$q_0 = \frac{\alpha g Q}{\rho C_p}$	buoyancy flux (m^2/s^3)
$N = (-\beta g d\rho/dz)^{1/2}$	brunt-Väisälä frequency (s^{-1})
$R_{aT} = \alpha g \Delta T H^3/\kappa_T \nu$	thermal Rayleigh number, where $\Delta T = T_b - T_u$
$R_{aTl} = \alpha g \Delta T_2 H^3/\kappa_T \nu$	local thermal Rayleigh number where $\Delta T_2 = T_b - T_2$, T_2 temperature at 2 mm from the bottom, α, κ_T and ν were taken at T_2.
$R_{aS} = \alpha g \Delta C H^3/\kappa_S \nu$	solute Rayleigh number, where $\Delta C = C_b - C_u$
$P_r = \nu/\kappa_T$	Prandtl number
$Sc = \nu/\kappa_S$	Schmidt number
$\tau = \kappa_S/\kappa_T$	ratio of diffusivities (Lewis number)
$R_i = \frac{\alpha g \Delta T h}{U_e^2}$	Richardson number
T	temperature (°C)
t	time (s)
U_e	entrainment velocity (m/s)
U_*	convective velocity (m/s)
X	horizontal coordinate (mm)
Z	vertical coordinate (mm)
PIV	Particle Image Velocimetry
CCD	charge coupled device
FFT	fast Fourier transform

Greek symbols

α	thermal expansion coefficient (°C^{-1}) – *uncertainty* ± 3%
β	saline expansion coefficient (m^3/kg) – *uncertainty* ± 3%
ν	kinematic viscosity (m^2/s) – *uncertainty* ± 2%
ρ	density (kg/m^3) – *uncertainty* ± 0.2%
$\Lambda = R_{aT}/R_{aS}$	stability parameter

Subscripts

u	upper
b	bottom
m	medium
∞	ambient

Theoretical and experimental studies (Weinberger, 1964; Hull and Mehta, 1987; Renyuan and Nilelsen, 1994; Husain et al., 2003; Choubani et al., 2010) showed that the efficiency of a solar pond in storing energy depends on the stability of the gradient zone (NCZ). Maintaining the state of the salt gradient zone (boundaries level and salinity gradient of NCZ) stable as its initial design is essential to successful operation of a salinity gradient solar pond.

Veronis (1965) used the linear stability theory to investigate the instability of a salt stratified layer. He considered a layer heated from below with free boundaries. He found the value of the critical thermal Rayleigh number for the stationary and the oscillatory regimes. The case of rigid–rigid boundaries has been also studied by Veronis (1965) and Sani (1965) using the non-linear theory. In our case, the gradient layer is confined in a cavity with a free upper surface. However, interesting results of Veronis (1965) and Sani (1965) are not adapted to our problem.

Turner (1968) investigated a thermohaline system under laboratory conditions, heating a linear salt solution from below at constant flux. He observed the formation of a mixed layer at the bottom. This layer grows until a second

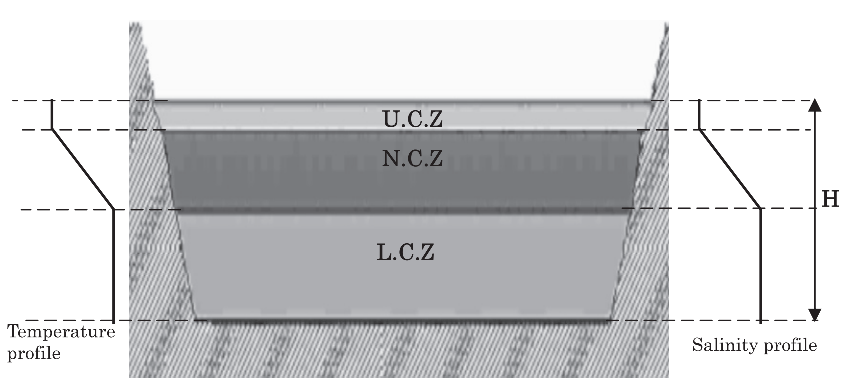

Fig. 1. Schematic of a salt gradient solar pond.