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Natural convection induced by absorption of solar radiation in the near shore region of lakes and reservoirs: Experimental results

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ABSTRACT

Natural convection induced by absorption of solar radiation in the near shore of lakes and reservoirs with a sloping bed is investigated experimentally utilising an open top triangular tank and a light source to simulate solar radiation. The present experimental investigation aims to examine the flow quantitatively for experimental parameters up to Rayleigh numbers one order of magnitude greater than that reported by Lei and Patterson (2002). Concurrent shadowgraph/Particle Image Velocimetry (PIV) technique is used to characterise the flow quantitatively for a number of experimental cases.

Three temporal flow stages, initiation, transitional and quasi steady are identified and three spatial sub-regions, conductive, stable convection and unstable convective, are observed, consistent with previous scaling and numerical results. Scales for the onset of instability, velocities along the slope and the movement of the plumes are also verified by the experiments.

1. Introduction

In the daytime, natural convection may play an important role in maintaining water quality, through influencing transport and mixing, in the near shore regions of lakes and reservoirs which are greatly protected from wind and are of large residence time.

Previous field observations (e.g. Adams and Wells [2], Macintyre [3], Macintyre and Melack [4], Monismith et al. [5], Rueda et al. [6], Schladow et al. [7], Sharip et al. [8], Verburg et al. [9], Wells and Sherman [10], Xing et al. [11]) have reported the importance of natural convection in controlling water quality. During the day, as solar radiation enters the water column, its intensity attenuates according to Beer's law. Although the attenuation rate depends on the turbidity and colour of the waterbody and also the wavelength of the radiation, it is common to assume a bulk attenuation coefficient in Beer's law (1):

$$I^* = I_0^* e^{-\eta^* d^*} \tag{1}$$

where I_0^* is the radiation intensity (W m^{-2}) at the water surface ($d^* = 0$), I^* is radiation intensity at the local water depth (d^*) and η^* is a bulk attenuation coefficient (m^{-1}). Here, and in the following, starred variables ($*$) are dimensional, and un-starred variables are dimensionless according the following scheme: time is scaled by $\kappa^{-1}\eta^{*-2}$, where κ is the thermal diffusivity, vertical length by η^{*-1}, horizontal length by the cavity length L^*, and velocities by $\kappa\eta^*$.

The solar radiation is approximately equally distributed over the water surface in the shallow and deep regions and heat exchanges between the water body and ambient are also distributed approximately equally over the two regions. However, the depth in the shallow regions is less than that in the deeper regions, and therefore the volumetric rate of heating there is greater. Consequently, the shallow regions become warm relative to the deep regions. This creates a horizontal temperature gradient, leading to a horizontal convective motion. In addition, as the incoming solar radiation penetrates the water column in the shallow regions, there may be residual radiation at the bed, where it is absorbed and assumed to be re-emitted back to the water body as a heat flux [12]. This heat flux produces an adverse temperature gradient at the bed which may become unstable. This instability creates vertical convective motions towards the surface in the form of rolls or rising plumes. Thus, in shallow regions, two convective flows may be induced by solar radiation; the horizontal convective flow together with the potential vertical convective flow control transport and mixing in near shore regions.

Farrow and Patterson [13] performed a preliminary study of the flow induced by a nonlinear temperature profile in a two-dimensional triangular cavity. They provided zero-order asymptotic solutions for the temperature and velocity fields of the flow development where the bottom slope approached zero. However, their study did not take into account the effect of horizontal conduction and advection on the flow as such effects could only be considered if a second-order solution was provided. In addition, the study explained the development of the

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horizontal convective motion, but did not investigate the impact of the temperature flux on the bottom boundary and its potential instability. An experimental investigation modelling the natural convection induced by the absorption of radiation in near shore regions in a cavity with a sloped bed was conducted using shadowgraph visualisation by Lei and Patterson [1]. The visualisation along with discrete temperature measurements in a number of locations in the bottom boundary layer revealed three stages of the flow development: initial growth, transitional, and quasi–steady. In the initial stage, the growth of the top and bottom boundary layers was observed, followed by three-dimensional convective instabilities in the form of rising plumes that characterised the transitional stage. The quasi–steady stage was observed by the quasi–regular appearance of plumes with reduced intensity. Another investigation was conducted by Lei and Patterson [14] to develop an understanding of the mechanism of the flow development through scaling analysis in a wedge. The study classified the overall flow in the wedge into three possible flow regimes (conductive, transitional, and convective) depending on the Rayleigh number. However, it was assumed in their study that the maximum water depth in the wedge was less than the length scale of radiation penetration depth ($1/\eta^*$). In addition, the dependency of the flow characteristics and regimes on the horizontal position was ignored because a fixed length scale (the length of the wedge) was used to simplify the problem. Mao et al. [15] improved the developed scales significantly by introducing two functions of critical Rayleigh numbers and a variable length scale to consider the dependency of the scales on the horizontal position. They illustrated four scenarios of the flow based on the bottom slope and the maximum water depth with the possibility of having multiple subregions in the domain in each scenario. Three different subregions, namely, conductive, stable convective and unstable convective were described, the presence of which in the domain depended on the global Rayleigh number. Further, it was found later that the horizontal velocity scale that had been developed by Mao et al. [15] for the stable convection region could also be used for a time-averaged mean flow in the unstable region at the quasi-steady state [16].

Naghib et al. [17] studied vertical natural convection induced by absorption of radiation in shallow regions of lakes and reservoirs where the bottom slope is zero. They described the flow development using concurrent shadowgraph/PIV measurements. Furthermore, the onset of instability, plume rise and plume rise velocity were characterised for a range of Rayleigh numbers over an order of magnitude and experimental results were compared with previously developed scales.

Thus, while there have been a number of analytical and numerical studies investigating the flow development on a sloped bottom subjected to radiation input through the surface, there has been only one reported laboratory study [1], with one Rayleigh number, and little quantification of the results in terms of the developing instabilities. Hence, this paper aims to provide experimental data on the flow development on the sloping bottom, over a wider range of Rayleigh numbers, and quantifying the flow properties and comparing these with the formerly developed scales. Finally, it is worth noting that this is one of several mechanisms which may influence mixing and transport in lakes. The aim here is to develop an understanding of this particular mechanism as part of the overall mix of forcing.

2. Experimental procedure

2.1. Experimental model and method

Although the bathymetry in the near shore of lakes and reservoirs is complicated, it is believed that the main features of the convective flow induced by the absorption of daytime radiation heating can be revealed using a triangular cavity as an idealised model. Therefore, many studies have used a triangular cavity model to investigate natural convection in near shore of lakes and reservoirs [1,13–16,18–21].

In the present laboratory study, experiments were conducted in an

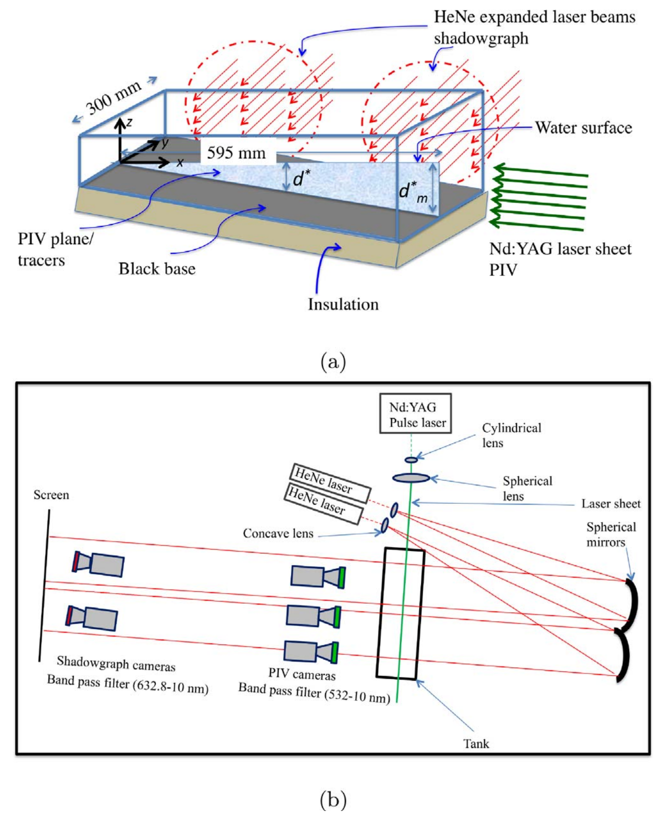

Fig. 1. (a) A schematic of the experimental tank arrangement, showing the shadowgraph set up and the positioning of the PIV plane. The local and maximum water depths are denoted by d^* and d^*_m, respectively. (b) The sketch of optical setup for concurrent PIV/shadowgraph. The spherical mirrors are slightly tilted in the vertical direction. The PIV cameras are at a slightly lower elevation than that of the HeNe parallel laser beams. Therefore, they are also slightly tilted in the vertical direction. Thus, the parallel HeNe laser beams for shadowgraph visualisation are not blocked by the PIV cameras.

open top (595 mm long and 300 mm wide) cavity filled with water as illustrated in Fig. 1(a), similar to that used in the study of Lei and Patterson [1]. The middle part of the transverse sidewall in the deeper end of the tank was made transparent for a width of 30 mm to allow the passage of the Nd:YAG laser sheet needed for PIV measurements. The tank has a sloped bottom with slope (A) of 0.1 giving a maximum water depth of 59.5 mm. The bottom heating due to the PIV laser is negligible as each laser pulse is of 1 µs duration, at a frequency of 1 Hz.

A Fresnel stage light with a 1000-W halogen lamp (3000 K colour temperature) and a maximum diversion angle of 25°, manufactured by Selecon PHILIPS, was used as the source of radiation to simulate sunlight. Applying a diversion angle of 25°, the spatial non-uniformity of the light intensity was less than 15% over the surface area, which is deemed to be acceptable.

A radiometer (LI-COR LI-250 with Pyranometer sensor) was used with an accuracy of 0.4% of the reading at 25 °C to measure the radiation intensity. Neutral density filters (manufactured by MidOpt) of diameter 150 mm were used in front of the light source to reduce the radiation intensity reaching the water surface by 50% and 25% in the wavelength range of 400–1100 nm so that experiments could be conducted over a Rayleigh number range of up to an order of magnitude variation without altering the spectrum of the incident light.

The longitudinal walls of the tank are made of transparent Perspex and the bottom of black Perspex which absorbs the residual light when the light reaches the bottom after its absorption by the water column, according to Beer's law as discussed previously. The bottom then re-emits the absorbed energy back to the water since the sloped bottom is insulated underneath by a 20 mm thick polystyrene layer.

Perspex has approximately the same thermal conductivity as water,