Experimental and Numerical Study on a Free Convection Layer Developing under a Water Surface

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ABSTRACT: We experimentally and numerically studied development and statistical properties of the free convective layer under a water surface. Velocity and temperature fluctuations were simultaneously measured by a laser-Doppler velocimeter and a fine thermocouple. Variances and correlations for the fluctuations were normalized by the heat flux and the thickness of the convective layer. The situation was numerically simulated by DNS. The calculated profiles of the variances were consistent with the experimental ones.


1 INTRODUCTION

Turbulence structure and transport process beneath the gas-liquid interface is important in air-sea interaction and in many industrial operations. The liquid-side turbulence near the surface is induced by wind shear and by buoyancy. The turbulence driven by wind shear has been investigated extensively in recent years (e.g., Liss and Merlivat\textsuperscript{(1)}), Komori et al.\textsuperscript{(2)}). However, the behavior of buoyancy-induced turbulence just beneath the liquid surface have not been well known quantitatively. In order to get detailed turbulence properties, we have done an experimental and numerical study on convective layer under a water surface. In our experiment, thermal convection was driven by cooling the gas-liquid interface by water evaporation.

2. EXPERIMENTAL SETUP AND NUMERICAL METHODS

The experimental set up is shown in Fig. 1. An open water channel was used as a working area. Evaporation from the surface of the area cooled the surface itself, and the buoyancy arose at the surface. In this way, thermal convection induced by buoyancy was developed under a free surface. The sidewalls and the bottom of the working area were doubled for heat insulation. The net cross section of the working area is $0.5\,\text{m} \times 0.4\,\text{m}$, and has 1.9m long. Hot water from the head tank flew the working area at a controlled flow speed (about 1.5 cm/s) and temperature.

Stream wise and vertical velocity components were measured by a laser-Doppler velocimeter (LDV). Temperature was measured by a fine thermocouple probe of 24 μm in
diameter. Velocity and temperature were simultaneously measured for 12~30 minutes.

The velocity and temperature field under a water surface is expressed using a system of rectangular co-ordinates. The x-axis is parallel to the flow direction and its origin is at the inlet of the working area. The y-axis is transverse to the flow. The z-axis is vertical and its origin is at the surface. The components of velocity fluctuation to x-, y- and z-axis are $u$, $v$, $w$, respectively. The letter $\theta$ denotes temperature fluctuation.

Numerical Calculation was done with a Boussinesq-approximated Navier-Stokes equation and a Cartesian grid. The space of the grid is regular for x- and y-directions, and its size is $0.01\,[m]$. But, it is non-regular for z-direction and becomes fine near the surface, and the minimum size is $4.5 \times 10^{-4}\,[m]$.

The following notation will be used:
- $\beta$: coefficient of thermal expansion,
- $z_i$: thickness of convective layer,
- $g$: acceleration of gravity,
- $Q$: heat flux,
- $\theta^*$ = $(Q^3 / \beta g)^{1/4}$,
- $w^* = (gz_i Q)^{1/3}$

3. RESULTS AND DISCUSSION

In the following drawings, experimental results will be put on the left side and numerical ones on the right side. Figure 2 is a top view. Flow was visualized by an electrolytic precipitation method. As a solder line was placed at 0.1cm below the surface, the photo shows the flow pattern near the surface. The dense white regions correspond to the water falling down from the surface. Thus their vertical velocities are positive. On the other hand, the dark regions are rising, and their velocities are negative. The strip structure seen in the photo is reproduced well by the numerical calculation in the Fig.2 right.

![Fig.2](image1)

Fig.2 Left: Photo of flow pattern near the surface. Right: Distribution of vertical velocity in x-y plane at $z=0.1\,[cm]$.

Figure 3, a side view, shows that mushroom like eddies are sinking, and the distances from the surface to their front seem to become large in proportion to the distance from the inlet of the working area.

![Fig.3](image2)

Fig.3 Left: Photo of side view. Right: Distribution of vertical velocity in x-z plane at $y=25\,[cm]$. 
The vertical profiles of the variance of temperature fluctuations are given in Figure 4. In the Fig. 4, the vertical profile of temperature variance is normalized by $\theta^*$. The heat flux $Q$ in $\theta^*$ was determined by the correlation method. The normalized profile was compared with that of the convection over a solid wall $^{(3)(4)}$. It is found that overall turbulence structure of temperature is very similar to a solid wall case. But, in the layer vicinity to surfaces, the difference becomes clear. In our result, the more approaching the surface, the larger the variance becomes. Meanwhile, the variance becomes zero at the surface of a solid wall.

Vertical profiles of the variance of velocity fluctuations are presented in Figures 5,6.
The correlation between vertical velocity and temperature is given in Fig.7.

From these figures, we think that the numerical simulation can reproduce the experimental situation well and give detailed information about statistical properties.

4. CONCLUSIONS
The laboratory experiment and the numerical simulation were done for the thermal convection developing under gas-liquid interface. Following conclusions were obtained:
1. The thickness of the convective layer increases proportionally to the lapse time.
2. In the layer vicinity to a surface, there are striking differences between the turbulence structure over a free surface and the structure over a solid surface.
3. Numerical results for the statistical properties quantitatively agree with the experimental ones.

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