Development and Decay of Columnar Vortex in two faces interface ; gas/liquid and solid/liquid

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ABSTRACT

Vortices terminating at free surface have been investigated extensively. Most of investigations, however, are focused on surface parallel vortices and little has been known about surface normal vortex or columnar vortex. Visualized experimental results utilizing LIF technique are discussed for the purpose of characterization of columnar vortex interacting with a clean and a contaminated free surfaces and a solid body interface in the present investigation. The results reveal that surface tension changes due to surface contamination although bulk viscosity remains constant and eventually the behavior of a columnar vortex interacting with a contaminated free surface and a solid body interface are totally different from the clean free surface case.

Key words: Vortex, Free surface, Stearic acid, Hemicyanin, Oleyl Alcohol, Surface tension, Surface viscosity, No-slip, Gas-like surfactant, Liquid-like surfactant, Solid-like surfactant

1. Introduction

The interaction of vortices with a free surface is a fundamental flow structure to understand a free surface turbulent flow. Vortices have a stable tendency that they connect to a free surface and many results of experimental studies(1) were reported about it. Lugt(2) showed analytically that all steady vortices attached to the free surface must be locally normal to the interface. However, most of these studies have concentrated on the interaction of initially surface-parallel vortices with a free surface and thus there is a gap in our understanding of how surface-normal (or columnar) vortices interact with and evolve at the free surface. These reactions are controlled by various conditions of the free surface. One of the most important results from these investigations is the strong significance of surfactants on the interaction. In most natural flows, the air-water interface is rarely free of surfactants. However, the concept of a free surface has generally meant that the external tangential stresses are negligible and the normal stresses are approximately constant. Such a free surface can rarely be observed in practice. The zero shear stress at a clean surface allows the normal attachment of vortices. However, a contaminated surface produces non-zero shear stress of the surface active materials (or surfactants). This has a significant effect on flow field. The interaction of vortices with a free surface has recently received extensive attention.

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For example, there is the modeling of CO_2, the cause of Global Warming, transport between the atmosphere and the ocean. The interaction of the atmosphere including CO_2 with the surface of oceans is controlled by interact process of vortices with a free surface: the free surface turbulence flow. Therefore, if we controlled this process, CO_2 in the atmosphere could effectively reduce. The objective of the present study is to identify the interaction of a surface-normal vortex and a free surface. So the present experimentation was performed various conditions: a clean surface in the absence of surfactants, a contaminated free surface by surfactants and a rigid, no-slip boundary.

2. Experimental apparatus and technologies

2.1 Experimental facility

This experimental facility was composed of two major components: a vortex generation system and flow visualization system. The vortex generation systems included water tanks, a pair of flaps, and control devices for the flap motion.

A schematic diagram of water tanks utilized in the columnar vortex generator is shown in Fig. 1. The water tanks were constructed of Plexiglas. The cylindrical tank was 250mm in diameter, 305mm high with a wall thickness of 5mm. The cylindrical tank was surrounded by a square tank with 350mm sides, in order to remove the optical distortion caused by viewing through the cylindrical surface.

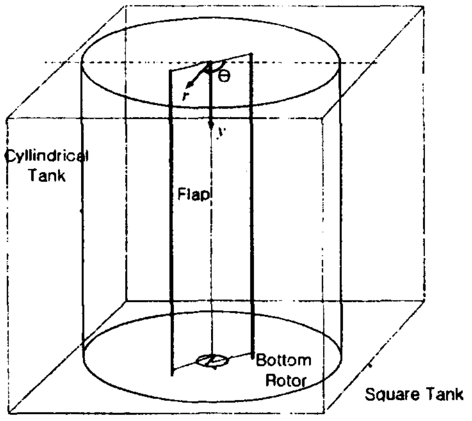


Fig.1 Schematic diagram of the water tanks utilized in the columnar vortex generator

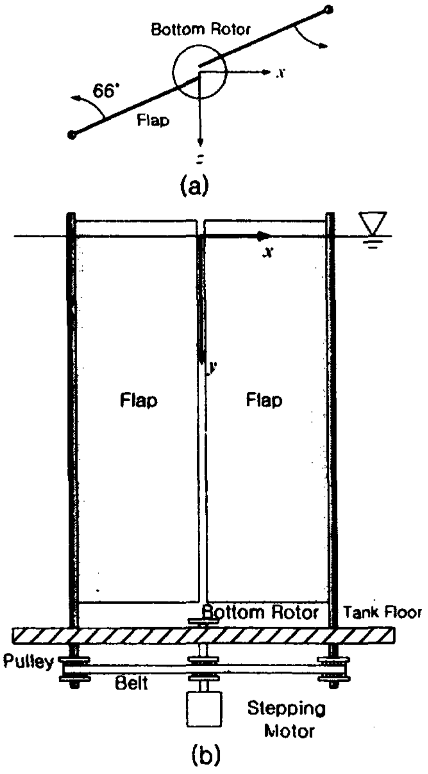


Fig.2 Schematic diagram of the vortex generator and the Cartesian Coordinate System: (a) plan view, (b) front view

The experiments were performed using the columnar vortex generator, illustrated in Fig. 2. This facility consisted of the computer controlled stepping motor and a pair of co-rotating flap (installed in the cylindrical tank). Each flap was made of stainless steel

(44mm wide, 254mm long, and 2mm thick) and was connected to the stepping motor by a shaft, a pulley, and a timing belt. Each flap sled a vortex sheet from its tip as it was rotated. The two vortex sheets rolled up together by mutual induction and formed a nearly two dimensional columnar vortex.

Originally, an instability was observed at the bottom of the water tank, which caused by the no-slip condition, and reached the free surface rapidly. The instability reduced the measurement period for the vortex interaction with the free surface. Subsequently, a rotor with a 30mm diameter was installed in the bottom of the water tank in order to delay the occurrence of the instability for as long as possible.

During the vortex interaction, the rotor was spun with a constant rotational speed of 0.65rev/sec. Using a laser and fluorescence dye, flow visualization were performed to examine the dynamics of the columnar vortex interaction with the free surface. The blue beam of a Ar-Ion laser(Spectra-Physics, Model 168, 5 Watt) was used for illumination. The laser beam was made into a light sheet through a 44mm focal length cylindrical lens. The light sheet was about 1mm thick. Flow visualizations were recorded with a CCD camera(Cooke, FlashCam) every 5 seconds.

2.2 Free surface experiments

The objective of the present experimentation is to study a effect of various free surface conditions to the vortex flow.

The schematic diagram of the experimental set up is presented in Fig. 3. The cylindrical tank was filled with water which was distilled using a distiller that removed ionized solid and organic compounds. To remove any possible surfactants remaining, high purity (99.9%) nitrogen bubbles were generated at the bottom of the tank. The bubbles burst at the free surface of the water and the absorbed surfactants become concentrated there before being drawn off by surface suction or over flowing. After the surface cleaning process, surface tension measurements were performed using a ring-type surface tensionmeter to confirm that the free surface was clean. The absolute error was of the order of ±0.1 dyne/cm. The bulk water temperature was kept at 24℃ during the surface tension measurement. The measured surface tension for the clean free surface was 72 dyne/cm, which is in agreement with the published value at the temperature of 24℃(3).

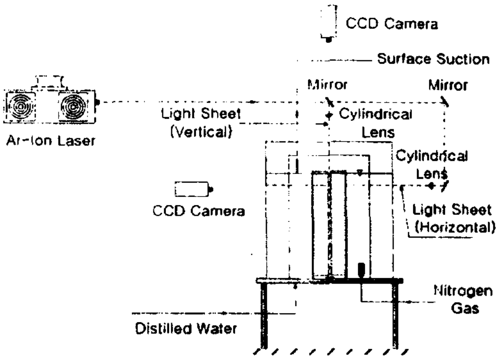


Fig. 3 Schematic diagram of the experimental setup for the flow visualization

For the experiments, two different surfactants were used to form insoluble monolayer on the free surface with each surfactant having a different viscoelastic behavior. The surfactants utilized were oleyl alcohol and stearic acid. In order to dilute the surfactant and allow a measurable amount to be deposited on a given area, HPLC grade benzene 99.9% was used as volatile solvents. This surfactants formed an insoluble monolayer with uniform concentration as benzene evaporated quickly.

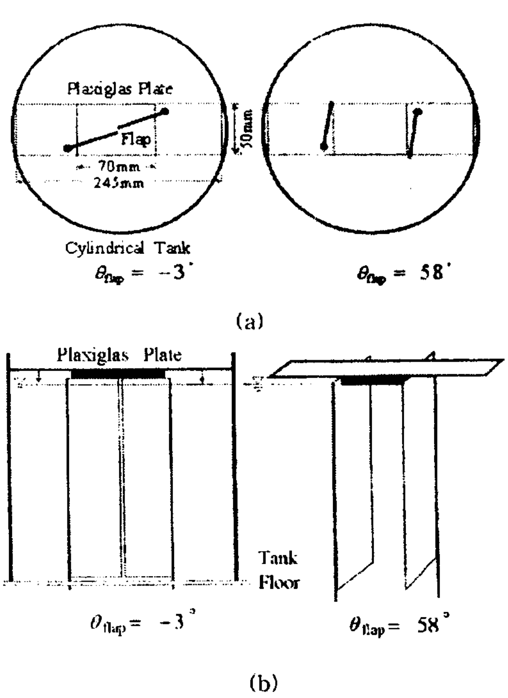
The concentration of oleyl alcohol ranged from 0.39 to 2.79 mg/m^2 with the corresponding surface tension of 71.1 to 38.6 dyne/cm and the concentration is saturated at 2.79 mg/m^2. The concentration of stearic acid ranged from 0.31 to 2.47 mg/m^2 with the corresponding surface tension of 71.6 to 60.1 dyne/cm and the concentration is saturated at 2.47 mg/m^2.

2.3 Solid plate boundary

A rigid, no-slip boundary condition was imposed on the top of the vortex following its generation. The experimental result under this boundary condition was compared to that of contaminated surface by surfactants. A Plexiglas, 50 × 70 mm with 2 mm thickness, was placed on the top of the flap, and a pair of extension plates were attached at each side of the Plaxiglas plate. see Fig. 1. The Plaxiglas plate was supported by the flaps and the attached extension plates made contact against the cylindrical tank wall. Therefore, the plate remained stable in that position during the initial stages of flap rotation and dropped down by gravity onto the free surface after the flaps had rotated approximately 61 degree. At the same time, the friction between the tank wall and extension plates reduced the falling off speed of the plate and made for a smooth contact of the plate with the free surface.

3. Results

3.1 Clean free surface



(a)

(b)

Fig 3. Procedure for establishing a rigid, no-slip boundary; (a) plan view, (b) front view. The flaps complete the rotation after 66° and the plate falls onto the free surface after 61°

Fig. 5 shows the velocity profile along the x-axis at z = 2 cm at the end of flaps rotation. The maximum velocity, $U_{\theta,c}$, at this depth is 1.16cm/sec with corresponding core radius, r_c, of 1.05 cm. Reynolds number defined as was calculated from this velocity profile. The Re is approximately 112. The Froude number, Fr, is 0.012 for the present vortex field. This low value of the Fr proves that because of gravity, the surface deformations are small and do not have a significant effect on the vortex interaction with the free surface.

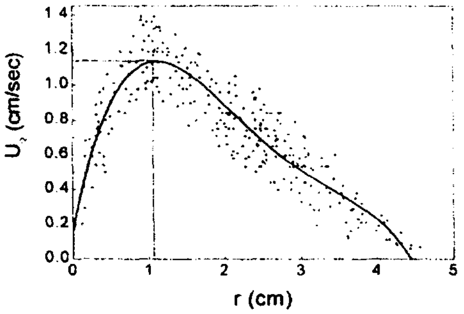


Fig. 5 Distributions of tangential velocity, U_θ vs. radius, r.

The visualized images of the vortex interaction with a clean free surface were recorded with CCD camera and are shown in Fig. 6 and 7. The photographs in Fig. 6 were taken in the cross-section plane at a depth of 2 mm below the free surface with the camera looking down at the light sheet. At time t = 0 sec, defined to be at the end of flap rotation, vorticity is apparently still shed and the vortex grows. As seen in Fig. 6, the growth of the vortex is impeded by the existence of the flap, and the vortex deforms into an elliptical shape. The photographs taken in the meridional plane are presented in Fig. 7. The dye streaks are normal to the free surface and the mirror image visible near the top of each image is due to total internal reflection at the free surface. Fig. 7 shows that the free surface remains essentially flat during the vortex interaction and that the vortex keeps coherent up to t = 20 sec.

3.2 Contaminated free surfaces

The response of a contaminated surface to fluid motion is different from a clean surface. In the present experiments, monolayers of oleyl alcohol and stearic acid were tested. Liquid-like surfactants such as oleyl alcohol exhibit a strong elastic behavior but have a relatively low viscosity. However, surfactants with high viscosities, such as stearic acid, which is known as a solid-like surfactant, may influence the interaction of the vortex with a free surface.

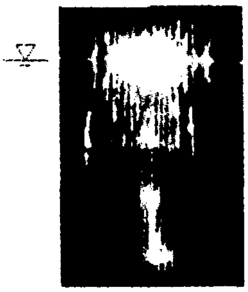
(a) t = 0 sec

(b) t = 10 sec

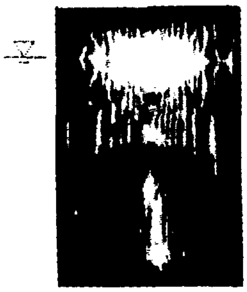
(c) t = 20 sec

Fig. 6 Sequence of the columnar vortex in the cross-sectional plane as it interact with a clean free surface z=0.2cm, Re=112, Fr=0.12

(a) t = 0 sec

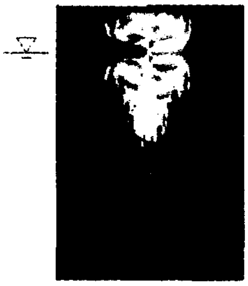


(b) t = 10 sec

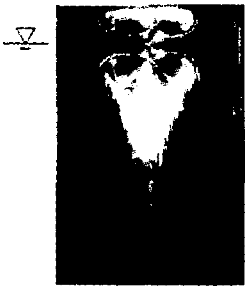


(c) t = 20 sec

Fig. 7 Sequence of the columnar vortex in the meridional plane as it interacts with a clean free surface



(a) t = 0 sec



(b) t = 10 sec

(c) t = 20 sec

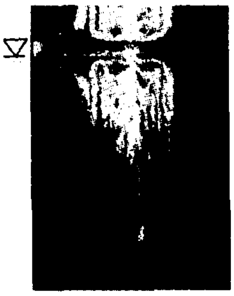
Fig. 8 Sequence of the columnar vortex in the meridional plane as it interacts with a contaminated free surface by stearic acid

Olely alcohol, which formed an insoluble monolayer at the clean free surface, was first utilized to observe its influence on the interaction of the columnar vortex with the surface. The visualized images in cross-sectional planes as well as meridional plane were found to be identical to those of the clean free surface, presented in Fig. 6 and 7. This is in agreement with the present observations that the columnar vortex is unaffected by the oleyl alcohol monolayer.

The visualized images of the interaction of the vortex with a contaminated surface by stearic acid are shown in Fig. 8. Fig. 8 (a) that is taken at the end of the flap motion shows the dye streaks underneath the free surface have converged toward the centerline. It also shows that a toroidal vortex begins to form underneath the free surface before the end of the flap motion and grows with time. The observed radially inward flow near the free surface is accompanied by a downward axial flow. This observation suggests that a boundary layer is formed at the free surface due to surface shear stresses and the resulting stress gradients toward the center of the vortex. The radially inward flow, caused by the stress gradients, is forced to change to a downward direction, since it clearly can not flow up and raise the free surface.

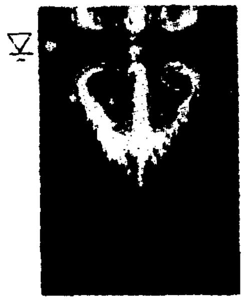
3.3 Rigid, no-slip boundary

The results for the solid wall case are presented in Fig. 9. The fundamental difference between the free surface covered by a viscous monolayer, such as stearic acid, and the free surface covered by the solid plate is the complete lack of motion at the solid plate boundary. The no-slip boundary creates a highly viscous boundary layer underneath the plate and does not allow any surface deformation. The velocity gradients across the solid plate boundary layer appear to be greater than those of the stearic acid case. Therefore, the toroidal vortex observed in Fig. 9 appears more completely rolled up than that in case of the contaminated surface.



(a) t = 0 sec

(b) t = 10 sec



(c) t = 20 sec

Fig. 9 Sequence of the columnar vortex in the meridional plane as it interacts with a solid wall.

4. Conclusions

The conclusions obtained from the present investigation are as follows;

1) When the free surface was clean, the surface-normal vortex was very nearly two-dimensional and remained surface attached during the observation period.

2) When the free surface was covered by a surfactant monolayer with large shear viscosity, the vortex lines were bent radially outward near the surface.

3) As a result of diverging vortex lines, a toroidal vortex appeared.

4) The columnar vortex was found to be a useful tool for qualitative evaluation of surface shear viscosity coefficient of surfactant system.

As a result of this study, surface rheology has a great influence to total flow field. In the case of natural water, such as river water and sea water, we must consider surface viscosity but bulk viscosity. Surface viscosity coefficient by surfactants produces the second fluid flow and can activate the contact and mass and energy transportation between atmosphere and ocean.

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