Team Assignment 3
John Murray
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The purpose of this project was to show how the flow of a fluid behaves near a surface. It is clear that the fluid flowing in the image is water, and that the flow is being disturbed by the presence of debris. The ripples on each side of the solid object physically show the effect of this disturbance. Though the flow behavior shown in the image seems quite simple, it is exceedingly difficult to model and predict the velocity profile of such a system. Nevertheless, this image reveals the viscous nature of liquids, as well as the strong effects of shearing.

The picture was taken of a natural phenomenon, but it could quite easily be replicated as shown in Figure 1.

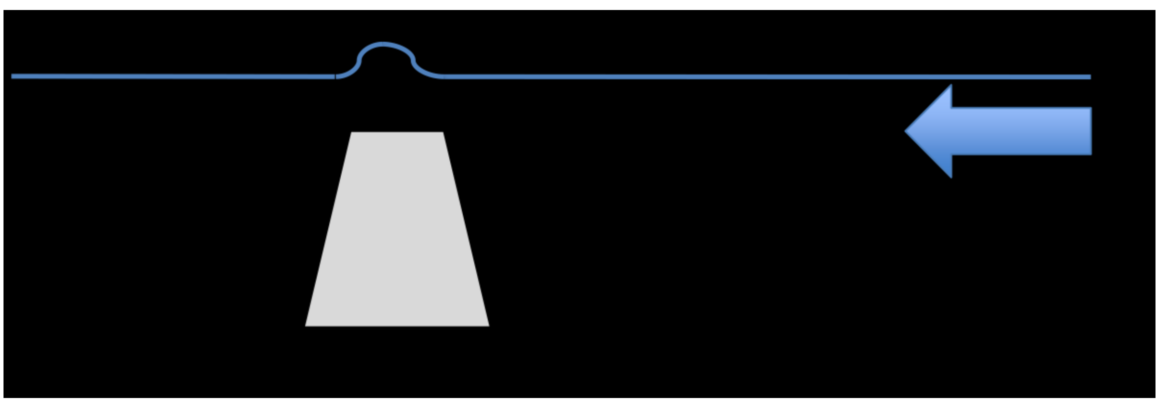

Figure 1: Side-view of shear flow testing apparatus

The height and depth of the channel, as well as the height of the disturbance, are dependent on the flow rate and fluid used by the experimenter. As liquid flows over a solid surface, a shear force exists between the surface and the fluid. Because the height of the fluid increases as it flows over the solid surface, the average velocity within the fluid must be decreased within this region. In order to quantify the decrease in average velocity due to shearing, the equation of momentum for the fluid must be considered. The following differential equation is a simplified version of the Navier-Stokes equation of motion [1], and is applicable to 2-dimensional, steady-state fluids.

$$-\mu \frac{d^2 v_x}{dy^2} = \rho g_z$$

This equation is based on a Cartesian coordinate system, where the x-direction is perpendicular to the flow and the z-direction is parallel to the flow, and v_z is the velocity of the fluid in the z-direction, g_z is the force of gravity in the z direction, μ is the viscosity of water, and ρ is the density of water. To solve for the velocity profile within the region of shear, two boundary conditions are necessary. One quite common boundary condition is called the "no-slip" condition, which means that the velocity of the liquid at the surface is considered to be zero. The other boundary condition is obtained from assuming that the shear stress at the gas-liquid interface must be zero. The resulting velocity profile is given by the following equation, and is related to the overall thickness of the sheared region (δ).

$$v_z = \frac{\rho g_z \delta^2}{2\mu} \left[1 - \left(\frac{x}{\delta} \right)^2 \right]$$

Because the maximum velocity given by this profile occurs at x=0, the velocity at any point in the fluid above the surface is some fraction of the free stream velocity. The maximum velocity of this flowing fluid is given by the following calculation, in which the angle of the flow with the horizontal is approximately 0.5°:

$$v_{\max} = \frac{\rho g_z \delta^2}{2\mu} = \frac{(999\,{}^{kg}\!/_{m^3})(9.8\,{}^{m}\!/_{s^2})\sin(0.5°)(0.01m)^2}{2(0.001\,{}^{kg}\!/_{m\cdot s})} = 4.27\,{}^{m}\!/_{s}$$

In order for the mass flowing through the system to remain constant, the height of the fluid channel must rise to accommodate a lower average velocity. The average velocity predicted by the above velocity profile is given by the following equation.

$$v_{ave} = \frac{2}{3} v_{\max} = 2.85 \, {}^{m}\!/_{s}$$

The average velocity of the fluid flowing over the debris is reduced by 33% compared to that of the free flowing stream. Because the mass flow rate must remain constant between these two regions, the height of fluid being sheared will increase consequently creating the ripples observed. This type of momentum analysis is very useful in determining velocity profiles for a number of systems.

The image was taken on April 25,2010 at 6:40 PM on a slightly slanted street in North Boulder (Glenwood Ave.). The ambient lighting was appropriate for capturing the contrast between the fluid and the debris, as well as the shadows throughout the ripples. The depth of slow-flowing water in the channel was quite low (~1-2 cm), and the direction of flow in the image is from right to left (as shown in Figure 1). Because the image was taken of a naturally occurring phenomenon, controlling the environmental parameters was very challenging.

The image of interested was approximately 3 feet from the camera lens, allowing for a field of view of about 2 feet. Using a Nikon D60 digital camera, the following exposure specifications were set: ISO setting – 250, aperture – F5.8, and shutter speed – 1/20 sec. The resolution of the image was quite low, however, with height and width of 640x480 pixels. This was mainly due to the decision to crop the photograph in such a way the flow phenomenon was the focus. Also, the contrast and definition of the image were enhanced using iPhoto.

This image clearly reveals the effects of shearing within a flowing fluid. A decreased average velocity in the fluid flowing over the surface causes an increase in the cross-sectional surface area, thus the creation of a ripple. Though the photograph was limited by the resolution of the camera used, the physical desired physical effects were successfully captured.

Reference:

1.) Bird, Byron R., Lightfoot, Edwin N., Stewart, Warren E. Transport Phenomena. 2nd Edition.