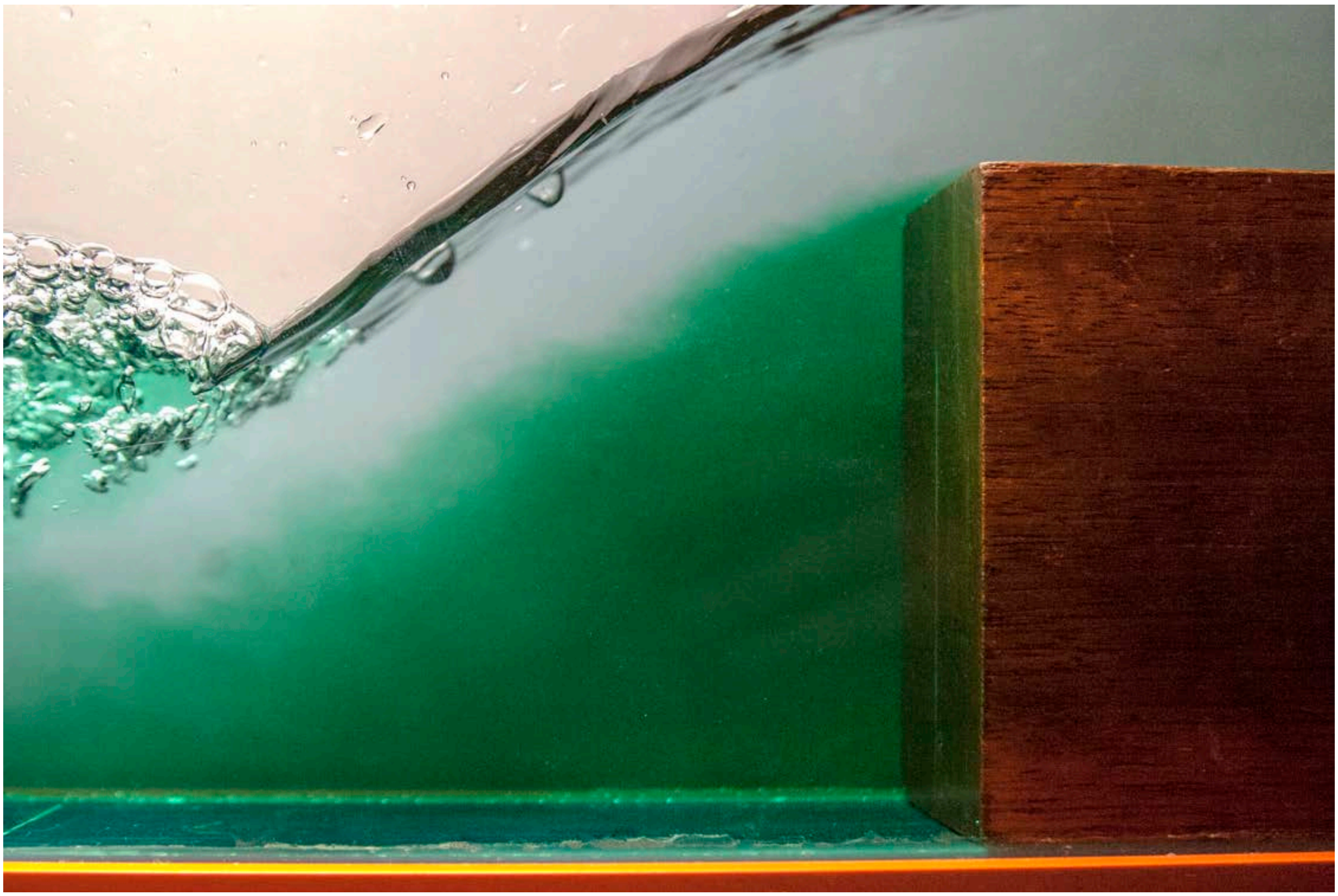
Group Project One

Slipstream Visualization



MCEN 5151:Flow Visualization

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Introduction

The goal of the group projects is to provide each student with a larger set of resources in order to produce more complex images. For this assignment my group decided to study flow of water through a flume. The flume is similar to a wind tunnel with the notable exception of using water instead of air. Originally, the group wanted to attempt to visualize a car model within the flume. We thought it would be interesting to consider flow over a model with the water traveling over the car with a similar Reynolds number as found when a vehicle travels through air in the real world. While a few of my fellow group members ended up using a small model that we purchased, I realized that a simple wood block simulated a semi traveling down the highway. After this realization, I knew that this would produce an interesting slipstream behind the "vehicle". Many people realize that drafting behind a truck can produce significantly improved fuel economy but I feel that it is rarely visualized. The goal of my image is to help show the effect of a large body traveling through a fluid and the wake it leaves.

The Physics behind the Image

The image used for this project contains many different flow phenomenon that can be studied including conservation of mass, turbulent mixing and slipstream effects. In order to begin analyzing the image, the Reynolds number will provide a basis for beginning the analysis. The Reynolds number is a unit-less ratio that describes the ratio of the inertial forces to the viscous forces (Benson, 2009). In reality, the Reynolds number helps to describe the type of flow that will be observed. The equation for the Reynolds number is below (Batchelor, 1967):

$$Re = \frac{\rho V L}{\mu}$$

ρ= density of the fluid
V=velocity of the fluid
L=Hydraulic Diameter
μ=dynamic viscosity

From this equation we can use published and experimental parameters to determine what type of flow was observed in the flume and relate this back to a real world flow experienced by something like a Semi-truck as seen in Figure 1. In order to find the two experimental parameters required to find the Reynolds number, I measured the channel's width and height while the pump was running. I also measured the volumetric flow rate using a volume meter and the time it took to flow 50 liters. The flow rate for the flume was approximately 1.2 L/s or a linear velocity of 0.19 m/s above the block. The head of the flow (with the block in the flume) was measured to be 181mm over a channel width of 77mm. Finally; the block was measure to have a height of 100mm. With these parameters, as well as using standard density and viscosity values for water at room temperature, the Reynolds number can be derived. With these measurements of the flow chamber taken, I first

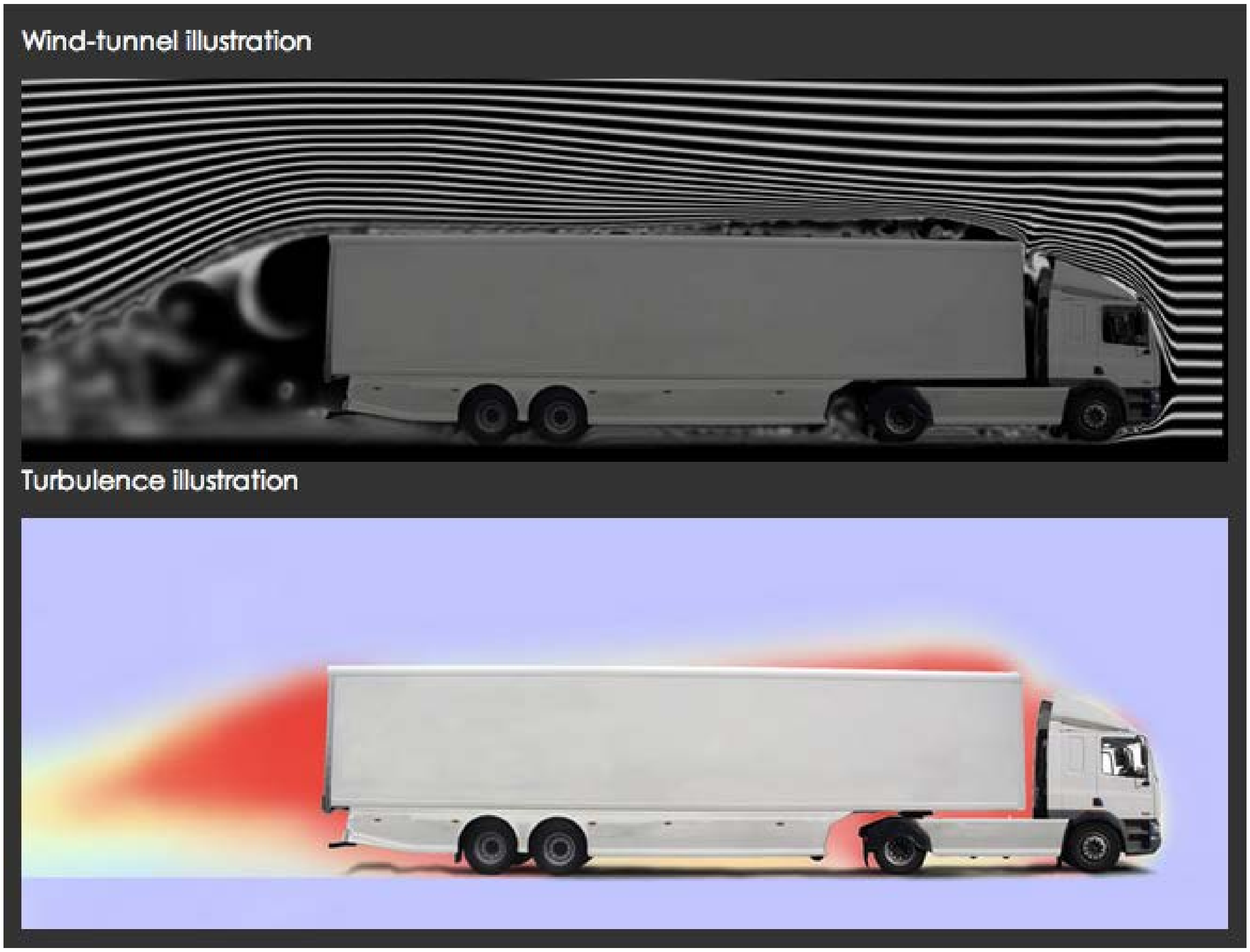

Figure 1-Flow around a semi truck (Don-Bur Ltd, 2014)

calculated the hydraulic diameter for the flow above the block using the equation below (Roseke, 2013):

$$HD = \frac{4hw}{w + 2h}$$

h=height of the fluid
w=width of channel

Using this equation, the hydraulic diameter for the water flowing through the channel is 104mm. The other required value that has to be derived is the velocity of the fluid in the channel. To derive this, one uses the following equation (Batchelor, 1967):

$$v = \frac{Q}{A}$$

v=Mean linear velocity of the fluid
Q=Volumetric Flow Rate
A=Flow cross-sectional area

Using the above equation, the mean linear velocity of the water was found to be 194 mm/s. Using published tables, I found the values for the dynamics viscosity and density at 20° C to be 1.002×10^{-3} kg/m*s and 998.2 kg/m^3, respectively (Crittenden, Trussell, Hand, Howe, & George, 2013). With all of the required values, the Reynolds number for the flow above the block was determined to be 20. This means that the flow above the block was in the laminar regime. This means that the fluid flows along streamlines or parallel layers with no disruption or mixing between the layers (Batchelor, 1967). When one looks at the captured image, this result makes sense for the water entering on the right. One can see that there is very little mixing between the boundary layers in the slipstream and the actual flow. As the flow gets further away from the wooden block, a laminar to turbulent transition takes place. The transition is a result of a transition from a subcritical flow to a supercritical flow back to a subcritical flow after the wooden block (Fernando, 2012). Super and sub critical flows are defined by a unit-less ratio called the Froude number that is the ratio of inertial and gravitational forces (Fernando, 2012). The Froude number is defined by the ratio below:

$$F = \frac{V}{\sqrt{GD}} \; where$$

V=Fluid Velocity

G=Gravitational acceleration

D=depth of the flow

The physical meaning behind whether or not a flow is sub or super critical is represented by the speed of surface wave propagation relative to the speed of the water; this is often referred to as the wave celerity (Furniss, et al., 2006). When the Froude number equals one the flow is considered to be critical, this means that the wave celerity is also equal meaning no disturbances are transmitted since the waves remain stationary. Supercritical flows are controlled upstream and disturbances in the flow are transmitted downstream. Subcritical flows are the opposite with flows being controlled downstream with disturbances transmitted upstream (Furniss, et al., 2006).

In the captured image, the flow has a Froude number of 6.8 meaning it is in the subcritical regime. The transition point (where the Froude number is one) can be seen at the top of the image where the flow begins to curve downward. Slightly before this point the flow begins to accelerate, moving away from the slower flowing water behind it. As the flow begins stretch due to mass conservation, the forces of cohesion (gravity and viscosity) start to become overwhelmed. As the water travels over the wooden block, there is a major increase in kinetic energy; a critical point is reached where the inertial forces overwhelm the cohesion forces (Fernando, 2012). This point is where the flow becomes critical and is marked by an observable dip in the flow of the water. This can easily be seen in the capture image. Since the flow continues to accelerate until hitting the bottom of the flume, we observe this critical flow until just after the point where the flow begins making contact with the flume surface.

Shortly after the flow reaching the flume surfaces, it begins to decelerate causing the flow to go from super to sub critical. At this point there is an observable hydraulic jump caused by the supercritical fluid reaching the subcritical fluid further down stream. This point is also marked by a major dissipation in kinetic energy that causes the hydraulic jump as well as turbulence (Fernando, 2012). This point can also be seen in the captured image where there is a hydraulic jump near the left of the image. This region of the image also experiences the expected turbulence as seen in the boundary layer between the green slipstream and the clear flow. After this point the flow continues down the flume remaining in a subcritical state. While the described physics are just a small part of the whole picture, I have tried to cover some of the major characteristics describing the flow captured in the image.

Creating the Setup

To create this image, my group requested usage of the flume within the Integrated Technology Learning Laboratory (ITLL) at the University of Colorado. After spending a few hours learning the tricks of the flume including how to control the flow rate, inject dye into the system, create good flows, and finally capture a well-lit, well-focused image. To create

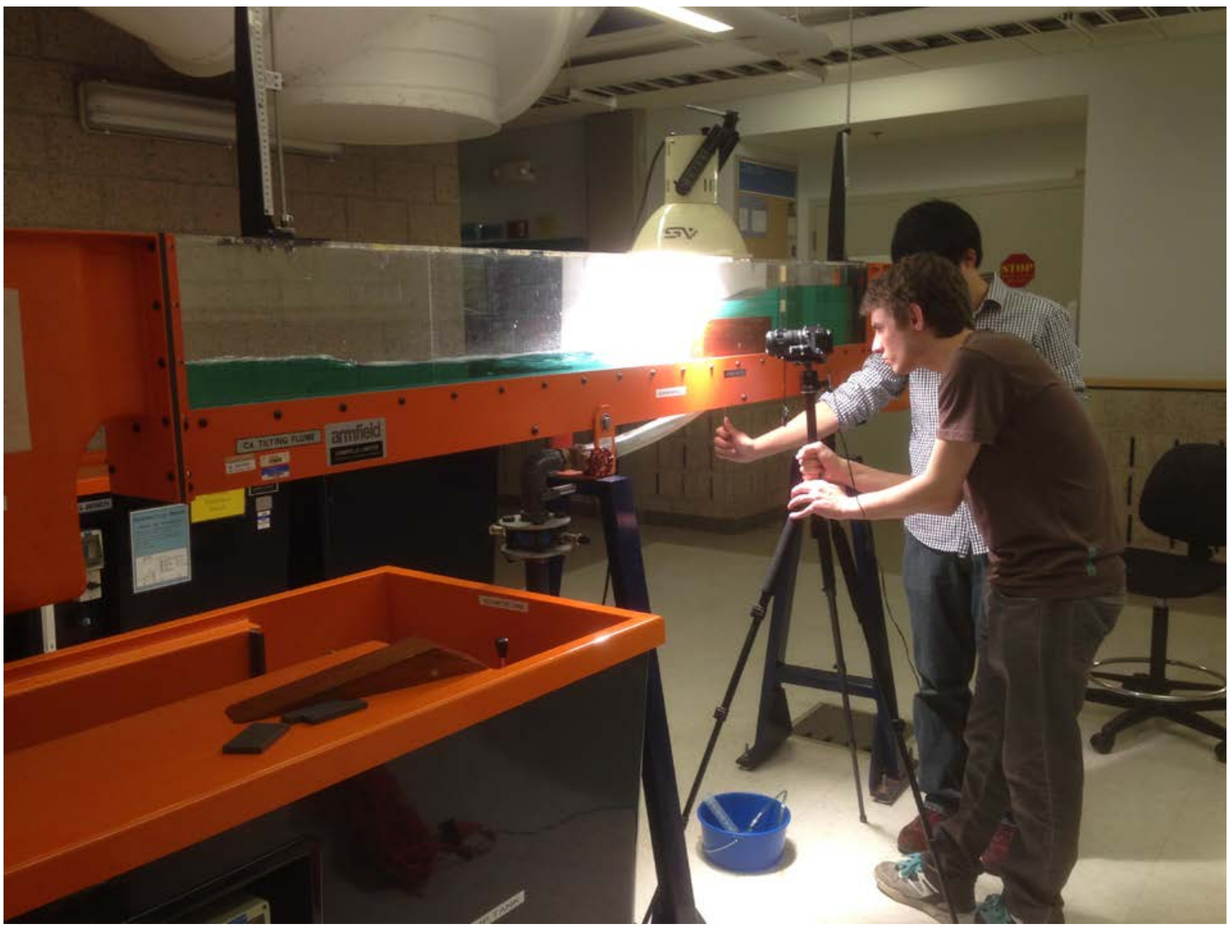

Figure 2 - Experimental Setup

this flow we used a block that was approximately 1/3 of a meter in length and 100mm tall. This wooden block was held to the bottom of the flow using a hook to ensure the entirety of the flow travelled over it. The flow rate for the flume was set to roughly 1.2 L/s Directly above the block the team used a single halogen lamp to light the setup. Green food coloring was injected into the flow using a medical syringe and a vinyl tube to ensure that there was as little disruption in the flow as possible. A tripod was used to hold the camera at a flume level, allowing for clear images to be taken repeatedly. This was necessary to ensure I could capture multiple exposures while the dye was being injected into the flume.

Capturing the Image

Due to the relatively fast traveling current, I had to setup my camera in a very specific way in order to capture a clean, well-focused, well-lit composition. I took hundreds of images while the dye was being introduced into the flume in order to gather as much data as I could. After reviewing these photos, I felt that the chosen image captures the slipstream well. The image was taken with a Canon EOS 10D. This camera has a 6.3 megapixel CMOS chip that is able to capture images at a resolution of 3072x2048 pixels (Canon USA, 2014). I used an ISO of 1600 to ensure that I could capture the image quickly. As seen in the original image, there is a slight bit of graininess as a result of the high ISO. Also as a result of the high ISO, I was able to capture images quickly with a shutter speed of 1/1500 second. This allowed me to capture clear, crisp images of the dye and bubbles being formed. Since the depth of field required for this image was relatively small due to capturing an essentially two-dimensional flow, I used a relatively low f-number of 5.6 to allow for a larger amount of light into the shutter. The lens used was a large range lens allowing for a focal length between 28mm and 135mm. For this image, I used a focal length of 38mm to allow the camera to be somewhat close to the flume while also maintaining a relatively wide field-of-view. Overall, I am extremely satisfied with the slipstream that I captured in the flume. While there are some imperfections within the image, many of these are a result of scratched or discolored walls of the flume itself. This is something that my group had relatively little control over and had to work around.

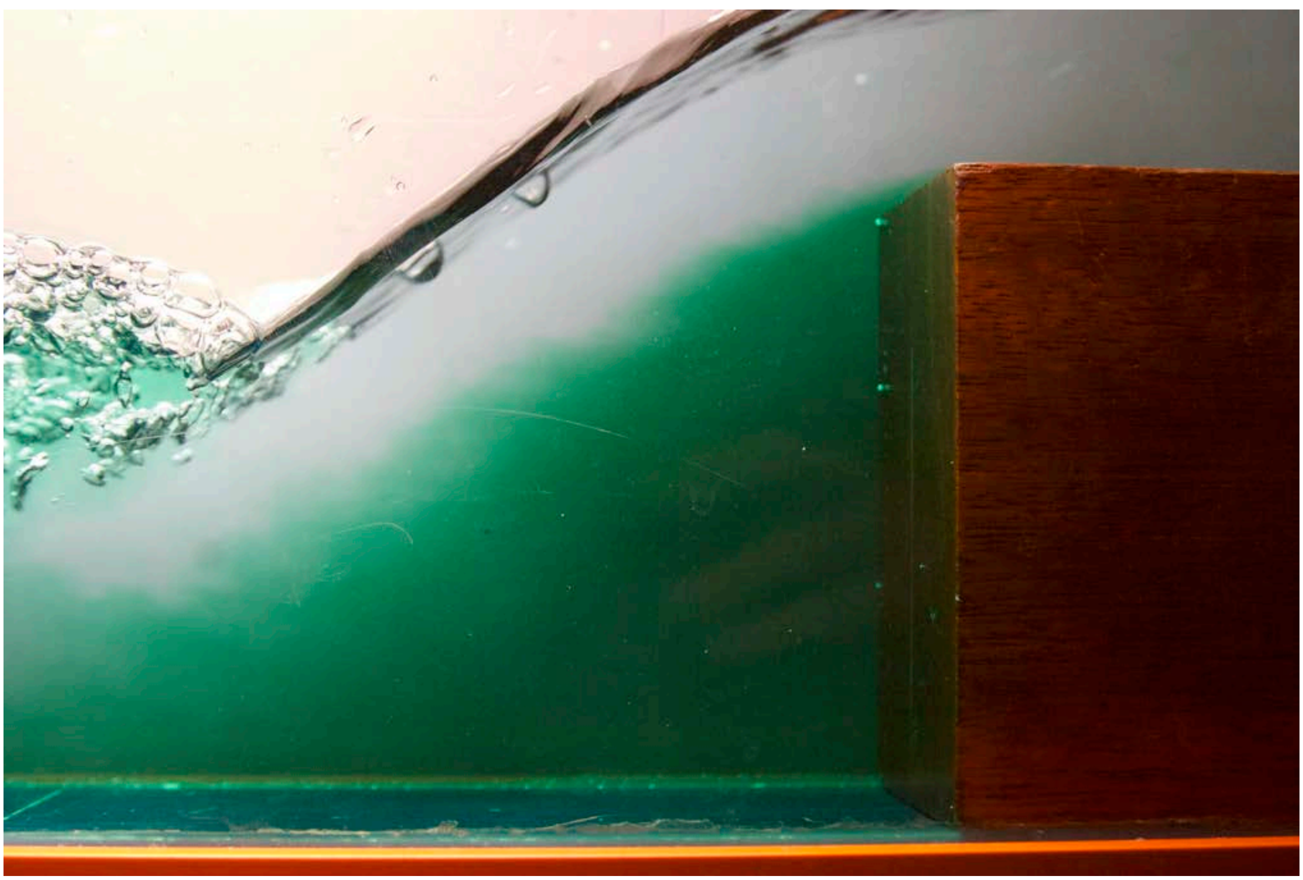

Figure 3-Original Captured Image

Post Processing

One of the big focuses of my post-processing was to help smooth the image. I used the spot healing brush to remove some of the random bubbles that were caught in various locations. I also smoothed over many of the larger imperfections that were present within the wall of the flume. These changes can be seen between the figure on the title page and Figure 3. In parallel with the cleaning up of imperfections throughout the image, I also lightened the image slightly. The reason for doing this was to allow for deeper contrast within the composition. I wanted to have a high contrast in order to bring out the dye captured within the slipstream as much as possible. Other than these few minor changes to the image, I kept true to the original image as I felt it did a great job capturing the flow.

The Image

This image captured something that many people know about but is often not captured in a clear, self-explanatory way. I am happy with the final image as I think that the image helps to visualize the concept of aerodynamics behind semi trucks quite well. There is also a fair amount of turbulent mixing towards the left of the image showing a transition from laminar to turbulent flow in a clear way. I really like the contrast of the image composition of the wooden block and the orange flume casing with the green water. I am also glad that the majority of the water was clear creating a nice boundary region between the two flows. Overall, I am extremely happy with the final composition and am glad my team chose to use the flume in the ITLL.

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