Flow Visualization around
Cylinder and Airfoil Using Dye Injection

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ME309: Fluid Mechanics
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1. Introduction

The experimentation with fluids and determining the fluid motion post collision with an object requires the calculation of Reynolds numbers. Before this method is used, the visualization of the flow and recording of flow data must be taken to make comparisons between the theoretical flow and actual flow. The characterization of the physical flow requires flow visualization, and directly comparing this to that of theoretical flow is the primary objective of this experiment. Flow visualization techniques have been used throughout history as a means to experimentally visualize the motion of a moving fluid and its reaction to external stimuli. In the past, the process was used with dye injection, as this was the only tool available—this was first done by Leonardo da Vinci during his work on turbulent flow within falling water. From then, various methods of flow visualization have been utilized, though the most notable still remains to be dye injection, tracers and other trackers may be more effective based on the experiment such as smoke injection for gas flow, PIV for finding instantaneous velocity in a fluid (mostly done in fluid research), and Schlieren Photography in visualization of fluid with differential density. Because of the ability to directly observe flowing patterns, flow visualization techniques are still used to observe flow phenomena in elementary experiments and understanding fundamental fluid dynamics in systems where the use of computational fluid dynamics may not be the most efficient method of observation.

The Reynolds number correlates with flow velocity, density, fluid viscosity and the geometry of the impacting object, along with the inertial and viscous forces, which in turn determine the properties of the resulting wake pattern. As the Reynolds number increases, starting from zero, the fluid motion drastically changes, easing off at turbulent wake and getting less predictable the higher the number gets. At specified number regions within the Reynolds spectra the described fluid motion alters drastically, i.e. \( \text{Re}_D < 1 \) is considered a creeping flow, \( 1 < \text{Re}_D < 4 \) is considered creeping flow with standing eddies, at \( \text{Re}_D > 40 \) the wake behind the cylinder break off and become oscillating vortices, getting more intricate, less predictable and
more chaotic as the Reynolds number increases. The calculation of Reynolds number is given by Equation 1

\[ Re_D = \frac{\rho U L}{\mu} \]  
(Eq.1)

Where:
- \( \rho \): Density
- \( \mu \): Viscosity
- \( L \): Characteristic length scale
- \( U \): Velocity

As seen with this formula, as there is a change in density, velocity of characteristic length scale, the Reynolds number will alter at a proportional rate; in the case of an altered viscosity, the Reynolds number will inversely change. Due to this, the same Reynolds number can be given to fluids with high viscosity as those with high density, high fluid velocity or high impact length, which is cause for increase in turbulence as speed increases. This effect is demonstrated in the many experiments and seen throughout fluid motion devices undergoing high speed tests. When the Reynolds number is low, viscous forces take over the fluid motion, when the Reynolds number is high then internal fluid forces cascade and conquer the fluid motion. For the purpose of simplifying Reynolds number experimental testing, the Reynolds number equation must be altered to fit the geometry of a cylindrical object. This can be seen in Equation 2.

\[ Re_D = \frac{U D}{\nu} \]  
(Eq.2)

Where:
- \( U \): Free Stream Velocity
- \( D \): Cylinder Diameter
- \( \nu \): Kinematic Viscosity

This modified Reynolds number equation gives view to the simplified motion of the fluid post impact with the object in basic observations of actual impact to compare to simple calculated observations. Because of the geometry, if the Reynolds number is calculated and known, then the resulting wake patterns can be predicted.

Reynolds numbers are a very powerful predictive method for describing fluid motion for simple object geometries. This is largely in part due to the simplicity of the modified equations which incorporate many of the fluid properties as well as incorporation of several applicable fluid assumptions (such as incompressible flow etc.) which allows for expected accuracy when compared to physical experiments. In the applied experiment, assumptions for constant fluid temperature, constant fluid density through dye injection, incompressible flow, and steady fluid velocity. These assumptions are necessary in the assurance that the Reynolds number may be used for proper prediction and description of the fluid flow, such as having constant fluid temperature to assure a constant fluid viscosity, as opposed to more complex fluid dynamics for proper system description.
Methods

For the experiment noted, the use of dye injection on variable size cylinders oriented parallel to the ground and perpendicular to the flow stream as well as dye injection onto airfoil on variable angles of attack were used to examine a visualization of fluid flow. The reasoning behind this was for allowance of comparison between observed phenomena and calculated Reynolds numbers based on known and recorded variable conditions set on the objects due to the dye’s ability to trace the flow accurately, inert to the fluid. Setup is shown in Figure 1.

![Figure 1: Lab setup for entire system.](image)

The system used in the experiment composed of a 6.35mm diameter cylinder, a 25.4mm diameter cylinder, a basic airfoil, a water tunnel and a dye injection mechanism. The water tunnel was activated after measuring the temperature of the water using a thermocouple to help in the characterization of viscosity. After setting the water speed to be 1.25 in/s in adjustment of the pump frequency to 10 Hz and waiting a 30 second period of time for the water to reach steady state, each cylinder was tested and the resulting wake pattern was photographed after dye was injected from the dye insertion tube and streamed onto the geometric center of the forward face of the object. The airfoil was then placed within the pump and subsequently tested using the same conditions, though the angle of attack was altered from 0° to 20° and tested for both angles as well as photographed. Following this, both cylinders underwent the same testing method but with an increase in fluid velocity of the water from 1.25 in/s to 3.0 in/s by switching input of the pump frequency to 25 Hz and waiting another 30 second period of time for the fluid flow to steady. Photographs were taken of each cylinder test, then all images downloaded and adjusted for report use.

2. Results

The acquired temperature was then used in the acquisition of kinematic viscosity from Appendix A table¹, as shown in Table 1. With this information gathered, along with that of the diameters and velocities (altered variables), the values could be directly implemented into Equation 2. Example calculations can be seen in Appendix B and results can be seen in Table 2.

<table>
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<tr>
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<th>Absolute Uncertainties</th>
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<tr>
<td>Temperature (T)</td>
<td>15.6 ± 0.1°C</td>
</tr>
<tr>
<td>Kinematic Viscosity (ν)</td>
<td>1.14*10⁻⁶ m²/s</td>
</tr>
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</table>

Table 1: Kinematic Viscosity determination based on temperature reading.
<table>
<thead>
<tr>
<th>Diameter (D)</th>
<th>Velocity (U)</th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td>1.25 in/s (10Hz)</td>
<td>6.35 mm</td>
<td>176.85</td>
<td>424.45</td>
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<tr>
<td>3.0 in/s (25Hz)</td>
<td>25.4 mm</td>
<td>707.41</td>
<td>1697.79</td>
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</tbody>
</table>

Table 2: Reynolds Numbers calculations based on variable diameter and fluid velocity

Reynolds numbers are broken down into ranges in the approximation of fluid motion for each segmented range. For $Re_D<1$ it is considered creeping flow, upwards of 4 then two standing eddies begin to appear. At $Re_D>40$ the wakes behind the object become unstable and break off and develop slow oscillations which roll up into two rows of vortices. $Re_D>80$ allows the elongated standing eddies to begin oscillation and periodically break off. This continues up until $Re_D>200$ where the vortex street becomes unstable and chaotic, almost turbulent in nature. After a value of 5000, periodic nature is completely absent and no pattern can be detected in terms of vortices.

3. Discussion

Because these ranges have been used with accuracy, it is beneficial to relate the analyzed tests to known fluid motions and then relate those motions to the specified range of Reynolds numbers. From that point, a calculated Reynolds number can then be compared to the range of each test, and then the degree of accuracy to describe fluid motion with Reynolds numbers can be gathered for each range. As a result of having known variables and the ability to record motion of the fluid, a direct comparison can be easily made observed and theoretical fluid motions. This resulting series of relations is seen in Figures 2 through 6.
In Figure 2, it is observed that the dye flow breaks off into shedding standing eddies. This vortex shedding gives correspondence to the Reynolds number range of $200 > \text{Re}_D > 80$ for the real world Reynolds number. When this is directly compared to the calculated Reynolds number for the situation involving a 6.35 mm diameter cylinder with 10 Hz (1.25 in/s) flow, it fits comfortably within the allocated range. These vortices can then be observed to follow that of Von Karman vortex sheet moving closer to the vortex center, it can be added that the vortices appear to be in a more periodic wake which gives indication that the real world Reynolds number is nearer to 200 than it is to the flowing 80.
In Figure 3, it is observed that the vortices have lost much of their periodic motion and are getting less stable, edging toward turbulence. The pseudo-chaotic motion, but with evidence of full reminiscent periodic motion still in place allows for the characterization of said system flow to be described within the Reynolds perimeter around of $Re_D= 200$ than that of $Re_D=5000$. When this is compared to that of the theoretical calculated number with the characteristics of adjusted speed to 25 Hz (3.0 in/s), it is seen that the calculated comes very neatly to the immediate range of physical importance.
In the observation of the 25.4 mm cylinder, the vortices are much more noticeable with easy analysis of the inner workings of each flow. The wake shedding appeared to be near periodic with Von Karman vortex sheet with slight chaos post collision. These properties show a Reynolds number close to 200, but when the theoretical value is applied, it is slightly off, edging closer to 1000. This discrepancy in value may be due to unforeseen factors in the flow which cascaded as the flow intensified around the geometry of the object. These factors may include variation in friction, alteration in fluid density, variation in temperature gradients within the fluid or imperfect collision among the object. The theoretical Reynolds number would suggest fluid flow which can be described as containing periodicity with addition of some chaotic motion and a small amount of turbulent wake shedding such as that of Figure 3.
When analyzing the picture of fluid motion amongst the adjusted speed of 25 Hz (3.0 in/s) along the large diameter cylinder, it becomes apparent that the flow has a higher velocity with the increase in turbulent wake and lack of collision amongst vortices. The properties ascertaining to periodicity seem to have completely vanished with randomized shedding which suggests a high Reynolds number, a higher number than that of the predictable Re_D of 200. This is near the turbulence level of Re_D = 2000^3. Then this value is compared to that of the calculated Reynolds, the theoretical matches closely with that of the seen, perfect conditions for the flow state with the real world fluid motion.
When analyzing the fluid at a zero angle of attack, it is immediately seen that the flow has very few alterations when passing along the airfoil, the flow is nearly smooth. This analysis allows the flow to correspond to the Reynolds range below 4, a creeping flow, as there is disregarded periodic motion (it is negligible compared to that of the horizontal motion), without evidence of significant turbulence. The fluid completely wraps around the airfoil with ease, and little loss of flow energy.

Figure 6: Smooth wake shedding across airfoil at 0° attack angle
Figure 7: Increased turbulent wake shedding across airfoil at 20° attack angle

When observing the airfoil at an attack angle of 20°, it can be seen that the flow across the airfoil gains chaotic motion as compared to that of 0° with signs of vortex shedding with addition of Van Karman vortex sheet forming across the upper edge of the airfoil. When observing the correlated Reynolds number, it is characterized as that of around 500 due to severely decreased periodicity (as opposed to that of Figure 4). The generation of some vortices puts a barrier on the range to which the Reynolds for this situation can be, halting it from achieving a larger value as the fluid motion would need to have a more turbulent aspect. When doing further analysis, it is seen that the fluid motion across the bottom of the airfoil allows for recombination with the fluid flow above the airfoil, thus creating a high pressure area which generates a degree of lift, unlike the flow for Figure 6.

When analyzing the full extent of every result as compared to their calculated counterpart, it becomes apparent that the Reynolds number approximation and its range sectioning is excellent at approximating the fluid motion across simple geometries. The results attained matched the expected with account that some observations are less precise with unaccounted factors coming into play during the recorded fluid motion.

In observation of each photograph cross compared to its other photographic counterpart, all had similar stagnation points which helped in the determination of the flow field from said point. Stagnation points are points on the geometry of the solid immersed within the fluid which the impact of the fluid is met with a perfectly matching object normal force leaving a static area of fluid post impact, thus leaving fluid without velocity. This, in turn, helps with the
development of a flow field which relatively describes the general fluid motion across the geometry of the object.

Another point to take note of is the separation point, a point where various forces come into play and allow for the generation of either laminar or turbulent flow and thus split the fluid motion into various flows, breaking the fluid up into separate fluid motions form that point. This helps with the development of chaotic motion and turbulent flow within flow fields, also being significant to the analysis of flow through streamlines and path lines of the fluid particles.

Inviscid flow if the flow of an ideal Newtonian fluid assumed to have zero viscosity. When compared to viscous flow, viscous has more laminar and turbulence as a result of friction across the object and within the fluid. In the experiment, the fluid was assumed to be incompressible (constant density) but had to be considered viscous as it is real as it directly caused the creation of each flow and generation of vortices. A flow can be considered inviscid when it is in stokes flow and the subsequent flow completely wraps around the object i.e. it is assumed to be inviscid when $Re_D<4$.

![Figure 8: Streamline sketch around airfoil at 20° attack angle](image)

The limitations experienced throughout these series of experiments are that of physical misinterpretations with our assumptions. This includes the possibility of gradient density, internal viscosity and temperature gradients within the fluid. A limitation which is caused by the experiment procedure is that of light diffraction and the infusion of multiple media to which the dye flow must be observed. However, these limitations are minimal if at all. The procedure used
sums up a simple way of narrowing down fluid flow visualization into a more predictable and applicable tool.

4. Conclusion

Although a variety of parameters provide in the overall motion of a fluid, the flow is primarily dependent on the relative velocity of the impacting object, the geometry of said object, and to the average temperature of the ambient fluid. In this manner, a Reynolds number can be calculated and through the number’s characterization, the resultant motion may be predicted. This motion can then be used in the correlation of the calculation to any viscous Newtonian fluid, as seen in these experiments.

References
2. *Lab1_Manual_v3* [PDF]. (n.d.). Purdue University.
Appendix A

Properties table from *Fox and McDonald’s*¹

<table>
<thead>
<tr>
<th>Temperature, $T$ (°C)</th>
<th>Density, $\rho$ (kg/m³)</th>
<th>Dynamic Viscosity, $\mu$ (N·s/m²)</th>
<th>Kinematic Viscosity, $\nu$ (m²/s)</th>
<th>Surface Tension, $\sigma$ (N/m)</th>
<th>Vapor Pressure, $p_v$ (kPa)</th>
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Appendix B

Reynolds Number Calculation Example

\[ Re_D = \frac{UD}{\nu} \]

For example, let \( U \) be 1.25 in/s and \( D \) be 6.35 mm

1.25 in/s translates into 31.75 mm/s

Converting \( U \) and \( D \) into meters gives us:
\[ U = 0.03175 \text{ m/s} \]
\[ D = 0.00635 \text{ m} \]

Because \( T \) was approximately 15\(^\circ\)C, using the Appendix A chart we can see kinematic viscosity is \( 1.14 \times 10^{-6} \text{ m}^2/\text{s} \)

When inserting these values in we get \( Re_D \) to be 176.853

Going onwards with other values, the other Reynolds numbers are attained.

Translations:
\[ U = 3 \text{ in/s} = 76.2 \text{ mm/s} = 0.0762 \text{ m/s} \]
\[ D = 25.4 \text{ mm} = 0.0254 \text{ m} \]
EXPERIMENT RAW DATA SHEET
LAB 1: FLOW VISUALISATION

Lab Group Member Names:
(1) Adalberto Canez
(2) Yu Cheng chin
(3) Dier Rem
(4)

Division Number: 4

RAW DATA

Water Temperature (°C) = 15.8 °C

PHOTO CHECKLIST:
_ Wake shedding photo for SMALL CYLINDER for 1.25 in/s
_ Wake shedding photo for SMALL CYLINDER for 3.0 in/s
_ Wake shedding photo for LARGE CYLINDER for 1.25 in/s
_ Wake shedding photo for LARGE CYLINDER for 3.0 in/s
_ Wake shedding photo for AIRFOIL for 0 degree angle of attack
_ Wake shedding photo for AIRFOIL for 20 degree angle of attack

TA Signature: [Signature]