Flow Visualization

MCEN 5151, Spring 2011

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Team Project 2

4/6/11

Vortex shedding off a back facing step in laminar flow.

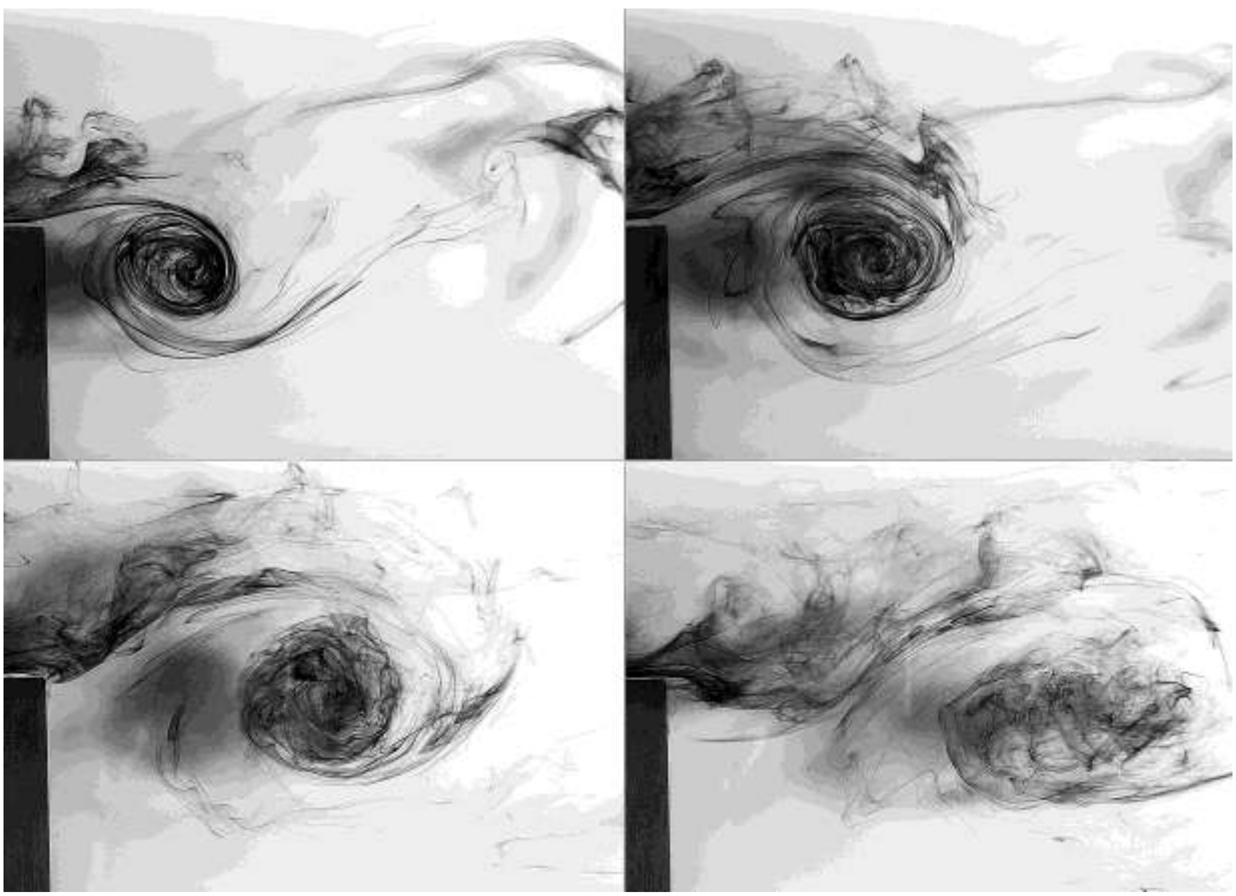


Figure 1, Vortex shedding from a back facing step in a laminar fluid stream.

Purpose: The main goal of this image is to show the formation and shedding of a vortex behind a back facing step. This was accomplished by taking a series of four images of die as it was carried by a laminar flow over right angle drop. Each image is taken 1 to 1.5 seconds apart. The series of images show interesting phenomena imposed by the vortex on the boundary layer of the step. Additionally the series of images gives insight into fluid diffusion.

Flow Apparatus: A horizontal flume and rectangular weir were used to experimentally replicate laminar flow over a backward-facing step. The weir filled the entire width of the flume, negating influences of flow around the weir, creating purely 2D flow. The level of the water was kept at a maximum. This minimized the effects free stream pressure gradient due to sudden expansion. Flow rate was adjusted to establish extremely laminar conditions. Die was injected up stream in the surface of the rectangular weir and carried downstream by the flow. Figure 2 depicts the geometry of the flow apparatus. Note, the length of the weir combined with the water height and flow rate minimize the effects of the forward facing step at the front end of the weir.

Figure 2, Geometric layout of the Flume

Flow: A basic analysis of a vortex forming and shedding behind a backwards-facing step.

Background: Vortices are circular or spiral fluid formations which originate from many different scenarios. A vortex can either be termed free or forced. In a free vortex flow velocity is greatest at its center, while a forced vortex has zero velocity at its center. [1] The flow experiment outlined above creates a forced vortex. It has a maximum velocity furthest from the center. Experiments Like these have been done for decades, perhaps centuries. These days people are interested in computational fluid dynamical algorithms which have the ability to accurately define scenarios of this type. The experiment examined here may seem fairly rudimentary however the asymmetry makes this this problem fairly complex and has therefore been of great interest over the past several years.

Vortex Formation: A vortex behind a backwards-facing step forms in the recirculation area seen in figure 3. It forms because of relative velocity differences from the flow above the step, or seen in figure 3 above height h and the initially stationary flow behind the step and below height h.

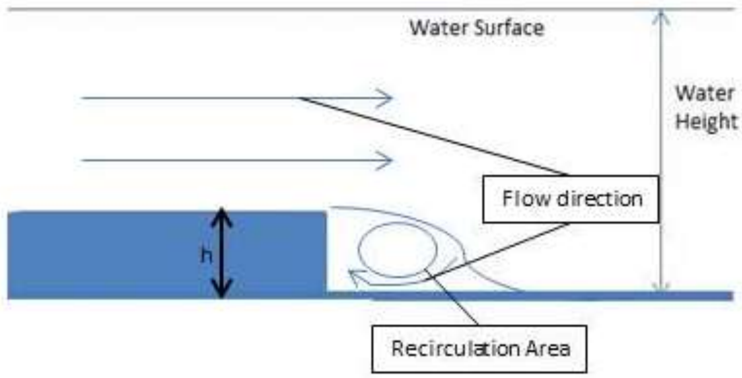


Figure 3, Relative flow directions above & below step level showing recirculation area.

As flow propagates over the step in a forward motion a backwards flow is established. As the relative velocity difference between these two opposite flow directions increases the recirculation area forms into a vortex. [1] Here the flow is circular in nature with velocity at zero in its center and increases radially. [1] Because of this the vortex is considered forced or rotational.

Vortex shedding: As time progresses pressure differences act on the vortex. The fluid above the vortex is moving. The fluid below the vortex is not. This creates low pressure above and high pressure below the vortex. This forces the vortex or recirculation area to rise up. The boundary layer which initially trips parallel to the surface of the step begins to angle upward. Eventually the vortex will be high enough where inertial effects of the upstream flow will push it down stream. This happens and the boundary layer then trips at the corner of the step. This phenomena is seen in figure 4.

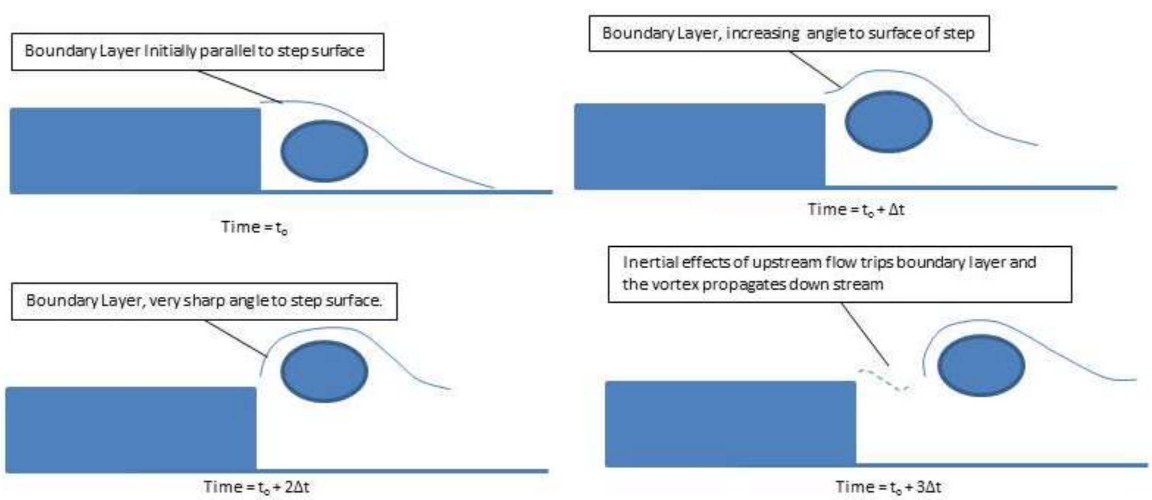


Figure 4, Boundary Layer changing with time.

Flow Observation: As the image sequence obviously shows the flow is extremely laminar. But to reinforce this fact the Reynolds number is calculated, here: [2]

$$\rho = 1.94 \frac{slugs}{ft^3} \ [2] \quad , \quad \mu = 2.730 * 10^{-5} \frac{lb \ sec}{ft^2} \ [2]$$

$$L = \frac{Crosssectional\ Area}{wetted\ perimeter} = \frac{0.082 ft^2}{1.148 ft} = 0.071 ft, \quad V = \frac{Q}{A} = 8.202 * 10^{-3} \frac{ft}{s}$$

$$Re = \frac{\rho V L}{\mu} \approx 42 \ [2]$$

$$Re < 500 \rightarrow Laminar\ Flow\ [2]$$

$$500 < Re < 12{,}500 \rightarrow Transitional\ Flow, Flow\ can\ be\ either\ laminar\ or\ turbulent.\ [2]$$

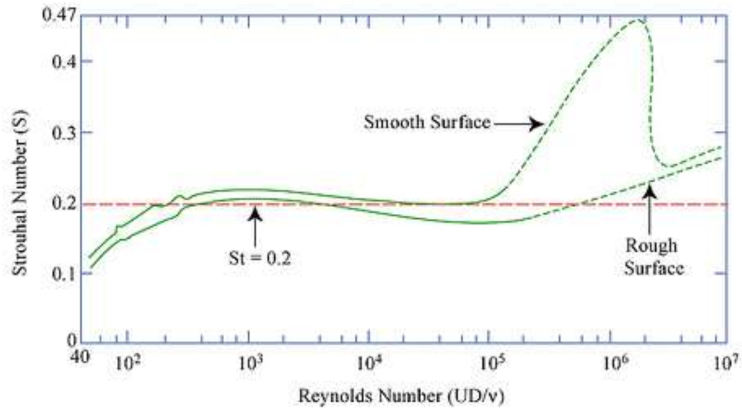
$$Re > 12{,}500 \rightarrow Turbulent\ Flow\ [2]$$

42 is less than 500 reinforcing the assumed laminar flow characteristic.

Additional information can be obtained by relating the Reynolds number to the Strouhal number. For low say Re ≈ 40 St can be estimated with the following plot. Say St is approximately 0.19.

$$St = \frac{fL}{V} \rightarrow f = \frac{St\ V}{L} = 0.022 Hz \ [3,4]$$

Giving rise to the frequency of vortex shedding off the step. [3] This meas a vortex will shed every 45 seconds. The time the four images span is only 4.5 seconds. In very laminar flow it takes a while for the flow to create a vortex, relatively the shedding of the vortex happens fairly quickly. It is not surprising the Strouhal number predicts this low frequency. This value is typically important when the fluid produces large loads on a body. This shedding then creates an oscillatory forcing function on the body. Vibration and fatigue are then the main areas of concern. [4]



Relationship between Strouhal number and Reynolds number for circular cylinders. Data from Lienhard (1966) and Achenbach and Heinecke (1981). S~0.21 (1-21/Re) for 40<Re<200, from Roshko (1955).

Observe figure 5. The above theory is reinforced by the image sequence areas of interest are highlighted below and explained in the following. Notice in the first frame the recirculation area and relative flow directions are defined. Frame two is taken 1.5 seconds later, the boundary layer angle has drastically increased and the vortex begins to travel upwards. The size has seemed to grow as well. Frame 3 shows the vortex propagating downward and the boundary layer beginning to trip off the corner of the step. Finally frame 4 shows the boundary layer completely tripped and the vortex propagating downstream. It also shows signs of fluid diffusion. Notice the lighter die tone. This is coincidental of fluid diffusion.

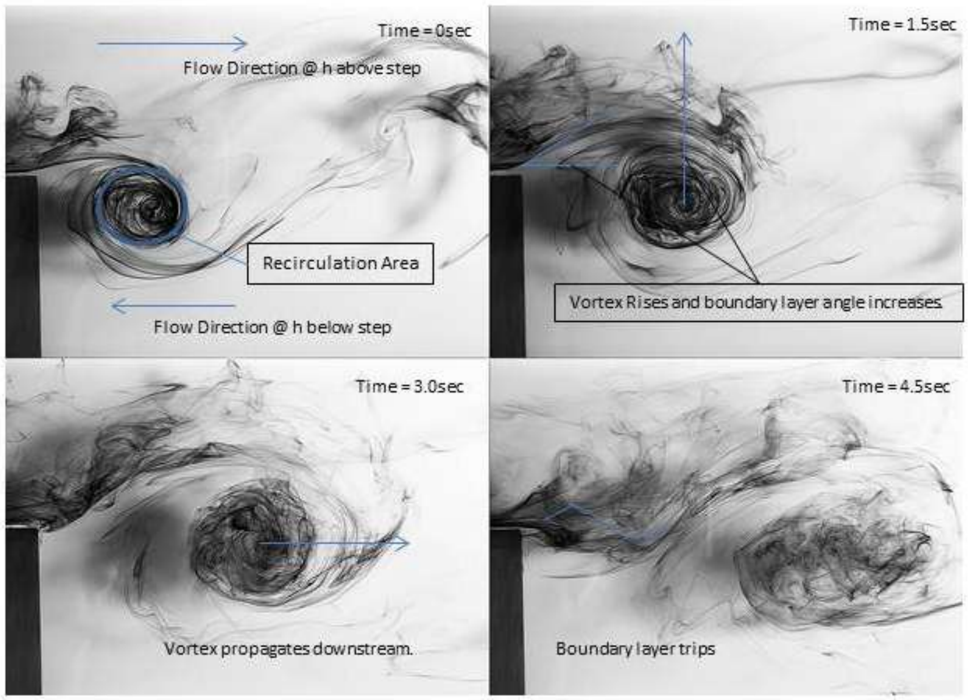


Figure 5, Image sequence showing fluid theory.

Numerical Analysis: Today computational fluid dynamics (CFD) is an area of research receiving lots of attention. Geometric setups such as the one imaged in this sequence are of specific interest because it drastically decreases complexity of the governing equations. Specific to the backwards facing steps the Navier-Stokes equations and the equation of continuity can be simplified to the following: [5]

$$\frac{\partial \rho u^2}{\partial x} + \frac{\partial \rho uv}{\partial y} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial \rho uv}{\partial y} + \frac{\partial \rho v^2}{\partial y} = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$$

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0$$

Where ρ is the density, μ is the viscosity and u, v are the velocities in the x and y directions respectively. [5]

Visualization technique: Each image was taken as follows. A white back drop was placed behind the flow. Halogen lights were positioned behind and to the right of the camera. There were orientated so they would produce no glare in the image. A uniform stream of die was injected in a stationary flow linearly to the level of the step. A laminar flow was then initiated and images several images were taken. Of those several images four were picked for the sequence. Each taken with the properties in Table 1. The images were then transferred to a grey scale. The image was mirrored horizontally creating the appearance of flow from left to right (instead of right to left) making the sequence conform with conventional western world thinking. The contrast and brightness were adjusted for each image to independently to highlight the important flow physics. All images were then transferred to the same layer in Adobe Photoshop to create a single image.

Image Info	*Data is for each individual image.	
Shutter Speed	1/80 sec	
F-Stop	f/3.5	
ISO	160	
Focal Length	18.0mm	
Pixel Resolution	X:	2780
	Y:	2352

Table 1, Meta Data for each individual image.

Image: This image sequence experimentally exhibits a vortex formation and shedding off a backwards-facing step. The flow is laminar and the eddy formed is captured by introducing die along a critical line of flow. I believe the image sequence to capture this nicely. A lot of image editing was done, the sharpest images were obtained when they were converted to black and white. I like color and had a hard time coming to terms with the simple grey scale. I would have liked to of obtained an image that had good color.

References:

[1] B. F. Armaly, F. Durst, J. C. R. Pereira, & B. Schonung, “Experimental and theoretical investigation of backward-facing step flow,” J. Fluid Mech. (1983) vol 127 pp. (472-493)

[2] H. Bengtson. “Uniform Open Channel Flow and the Manning Equation.” Continuing Education And Development Inc. CED Course No. C02-021

[3] D. Wee, T. Yi, A. Annasqamy, & A. F. Ghoniem, “Self-sustained oscillation and vortex shedding in backwar-facing step flows: Simulation and linear instability analysis.” Physics of Fluids Vol. 16 no. 9 (2004)

[4] F. K. Browand, “An experimental investigation of the instability of an incompressible, separated shear layer.” J. Fluid Mech. (1966) vol. 26 part 2 281-307

[5] I. E. Barton, “The entrance effect of laminar flow over a backward-facing step geometry,” International J. For numberical Methods in Fluids, Vol. 25 (1997) 633-644