A Couple of Fluid Mechanics Brainteasers

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Abstract

This paper describes two fluid mechanics demonstrations which are presented to the class in the form of puzzles or paradoxes. Both demonstrations use very simple apparatus to dramatically show that considering only changes in a flow's linear momentum may not be sufficient to determine the flow forces acting on a body; i.e., pressure forces may be important. In the first demonstration pressure forces are significant because of the deceleration of the flow. Pressure forces in the second demonstration arise from both the flow's acceleration and mechanical energy dissipation and very nearly balance the change in linear momentum.

Introduction

Most students consider fluid mechanics to be one of their more difficult courses, finding it too abstract and mathematical. It becomes for many a dry exercise in manipulating series of equations. In an effort to counteract this mindset and at the same time offer a much-welcome respite from the normal class routine I introduce a limited number of demonstrations and puzzles.

My procedure is to describe the puzzle using a sketch on the blackboard, and then ask the class to think about what should occur. I tell the students not to guess based on a gut feeling, but to anchor their prediction on fundamental principles of fluid mechanics. After some class discussion I demonstrate the puzzle using the simplest of apparatus. Invariably, the outcome is at odds with the students's predictions. I then guide the students to resolve the discrepancy by asking certain pertinent questions. This results in a lively exchange of ideas and a deeper understanding of fundamentals.

Blowing can cause attraction

This puzzle is given to the class after the fundamental equations of continuity, force/linear momentum, and Bernoulli have been covered.

The demonstration uses a large sewing machine-thread spool, 1 1/2 inches in diameter at the bottom and 3/4 inches in diameter at the top, with a 3/8 inch diameter center hole and two paper disks, 1 1/2 inches and 3/4 inches in diameter. See Figure 1.

I tell the class that I'm going to hold the spool vertically with its small end up, put the small paper disk on the small end, and blow hard through the center hole from the bottom. As the class expects the disk is blown off the spool.

Next, I hold the spool vertically with its large end up and put the large paper disk on the large end. Then I blow as hard as I can through the center hole of the spool. This time the disk remains in contact with the spool and is not blown off. I then put the large paper disk on a table and the large end of the spool on top of the disk. Blowing hard through the spool hole I lift the spool, and the disk stays attached to it. Clearly, blowing causes repulsion of the small disk and attraction of the large disk.

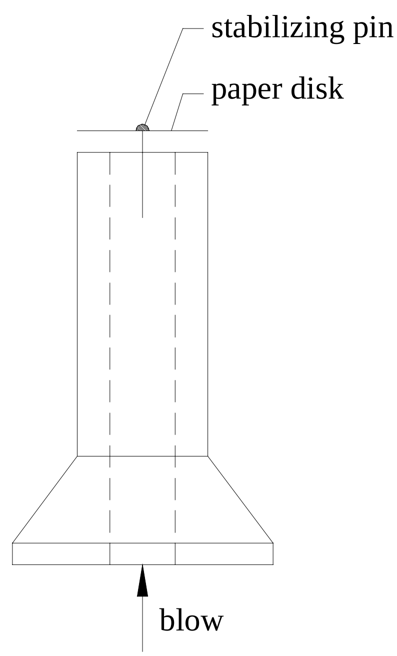

Figure 1. Spool with paper disk.

The resolution of the puzzle is that the class is focusing only on the repelling force caused by the change in direction of the flow's linear momentum which occurs at the center of the disk, and not considering the radially-outward flow from the center. This radially-outward flow decelerates as the cross-sectional area increases, causing the pressure to increase as given by the Bernoulli equation. The pressure is atmospheric at the outer edge of the disk, and thus must be below atmospheric in the interior. There is a partial vacuum in the passage between the disk and spool. Atmospheric pressure acts over the outside surface of the disk resulting in a net attractive pressure force between the disk and spool.

The result depends on the diameter of the disk relative to the diameter of the center region where the flow turns. If the disk diameter is too small, the partial vacuum does not act over enough area to overcome the repelling force at the center caused by the change in direction of the flow's linear momentum there, and the disk is repelled.

It helps the demonstration to have a common pin protruding through the center of the disk into the spool hole to stabilize the disk. Without the pin the paper disk has a tendency to float laterally off the spool due to the slightest skewing of the disk surface relative to the spool.

Feynman water-sprinkler puzzle

This puzzle is presented after the class has studied internal flows with frictional and other types of mechanical energy dissipation.

The puzzle was posed by Nobel Prize winning physicist, Richard Feynman, in his book, *Surely You're Joking, Mr. Feynman* [1]. Everybody knows the motion of a rotary lawn water sprinkler. Feynman, when a graduate student at Princeton, wondered what the sprinkler motion would be if the sprinkler were fully submerged in water, and the water sucked in through the sprinkler nozzles. The answer to this question can be obtained through a straight-forward application of the steady-flow energy equation or Bernoulli equation extended to include mechanical energy dissipation.

The puzzle can be simply demonstrated in class using a length of Tygon tubing formed into an L-shape by being taped to a short, bent piece of wire. Above the wire the tube is flexible and easily bends. The tube is supported by a wood stick. See Figure 2.

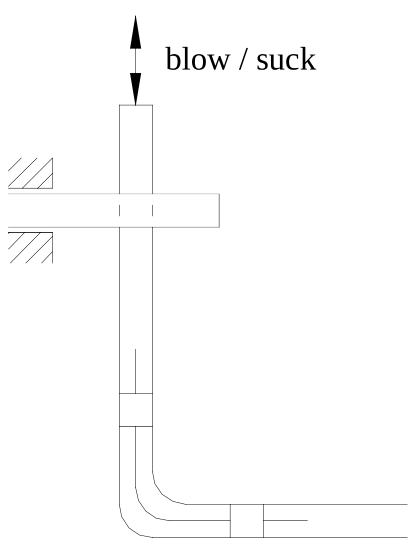

Figure 2. Flexible, L-shaped tube.

I tell the class that I'm going to blow through the top of the tube; what movement of the flexible tubing should result? Everybody agrees that because of the change in direction of the flow's linear momentum at the bend there will be a force acting on the tube opposite in direction to that of the leaving flow. When I blow through the tube, it quite noticeably moves opposite in direction to that of the leaving flow, exactly as predicted by the class.

I then tell the class that I'm going to suck air in through the top of the tube, and what movement of the tube can now be expected? The change in direction of the flow at the bend will still give a force in the same direction as before; i.e., to the left in Figure 2. However, when I suck air in through the tube there is no perceptible movement of the tube.

The solution to the puzzle is that when the flow is expelled, it leaves the tube at atmospheric pressure, and there is no net pressure force acting on the tube. The only force acting is that due to changing the direction of the flow at the bend. However, when the flow is sucked in, it enters the tube at a pressure less than atmospheric due to two effects:

i) Acceleration of the motionless, ambient air into the tube and
ii) Mechanical energy dissipation associated with the flow entering the tube.

The pressure drop associated with the acceleration of the fluid from zero velocity to the flow velocity in the tube, V, is given by the Bernoulli equation as $1/2\rho V^2$ where ρ is the fluid density. The mechanical energy dissipation is caused by boundary layer separation and the formation of an eddying flow at the lip of the tube. This mechanical energy dissipation has been found experimentally to result in an additional pressure drop of about $1/2\rho V^2$ [2]. Thus, a pressure drop due to the combined effects of flow acceleration and mechanical energy dissipation of about ρV^2 occurs at the tube entrance.

This pressure drop acting over the cross sectional area, A, of the tube results in a net pressure force of about $\rho V^2 A$ acting on the tube in a direction opposite to that of the flow; i.e., to the right in Figure 2. When this pressure force is combined with the force caused by the change in direction of the flow's linear momentum at the bend, $\rho V^2 A$, which acts to the left, the net flow force acting on the tube is so small that there is negligible movement of the tube.

Feynman, in his book, doesn't resolve the puzzle. He describes an experiment in which he immersed a sprinkler in a large glass carboy full of water, and pressurized the water with compressed air to force it into the sprinkler. The carboy shattered under the high pressure dousing him with water and shards of glass. Feynman ends the chapter here, obviously more taken with the failure of an early experiment of his than the answer to the puzzle.

Bibliography

1. Feynman, R.P., *Surely You're Joking, Mr. Feynman*, Norton, New York, 1985, pp. 63-65.

2. Idelchik, I.E., *Handbook of Hydraulic Resistance, 2e, Hemisphere, New York, 1986, pp. 113-114.*

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