Radial Momentum, Bernoulli and Lift

Ed Seykota
1060 Sunflower Trail, Austin TX 78745
e-mail: Seykota.Ed@gmail.com

"It would be better for the true physics if there were no mathematicians on earth."
-- Daniel Bernoulli (February 8, 1700 – March 17, 1782)

This paper claims that physics textbooks, the internet, science museums and even NASA incorrectly explain the phenomenon of lift by misapplying Bernoulli's Principle. Thus they are, ironically, validating Bernoulli's quarter century old proclamation about mathematicians. This paper also proposes a replacement theory to explain lift: namely, Radial Momentum.

The misapplication of Bernoulli's Principle rests on the incorrect assumption that lift occurs with incompressible (constant density) fluid. This paper claims this assumption is incorrect and that, indeed, the decrease in density that attends radially expanding fluid is essential to the explanation for lift.

1. Introduction

Fig. 1.1. Daniel Bernoulli

Daniel Bernoulli, son and nephew of the mathematicians Johann Bernoulli and Jakob Bernoulli, finds further inspiration from Sir Issac Newton (1642-1727) and Leonhard Euler (1707-83). From 1725-1749 Bernoulli wins prizes for work in astronomy, gravity, tides, magnetism, ocean currents, and the behavior of ships at sea. Around 1738 he writes Hydrodynamica, establishing the basis for the kinetic theory of gases. He discovers how to measure blood pressure, considers the basic properties of fluid flow, pressure, density, and velocity, and presents the fundamental relationship now known as the Bernoulli Principle.

Thousands of Internet sites, many educational institutions and popular textbooks all account for lift with the Bernoulli Principle. Typically, they interpret Bernoulli's Principle as: "high velocity causes low pressure." They use this relationship to account for a variety of lift phenomena, such as with airplane wings, curve balls in baseball, ping-pong balls sticking in funnels, perfume atomizers, levitators and other such devices.

Figure 1.2 shows the standard textbook diagram for lift. It generally accompanies the explanation that the flow over the top is faster than the flow under the bottom so, by Bernoulli's Principle, the pressure above must be less than the pressure below.

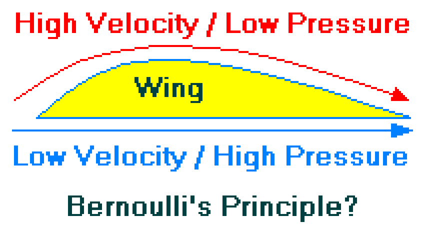

Fig 1.2. Standard Textbook Diagram for Lift

This paper disputes this explanation by showing that it incorrectly assumes incompressible (constant density) fluid. This paper then proposes that the theory of Radial Momentum provides a much better explanation, one that includes compressibility as an essential component of lift.

2. The Bernoulli Principle

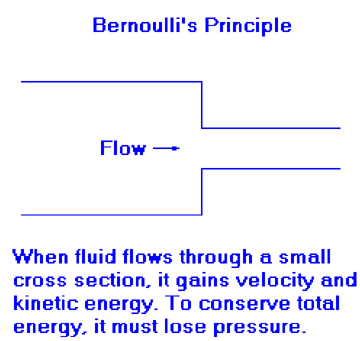

Fig. 2.1. Bernoulli Principle

The Bernoulli Principle is a statement of energy balance. It states that for certain conditions (steady flow, no friction and incompressible fluid), the sum of the thermal, kinetic and gravitational energies is constant at all locations. Thus, for fluid moving through a system of pipes of varying cross section, the fluid that moves through narrow pipes, moves faster and has lower pressure while the fluid that moves through wide pipes moves slower and has higher pressure. The derivation of this principle is:

$$E_T + E_K + E_G = k$$

For systems that do not involve gravity change, this becomes

$$E_T + E_K = k$$

Thermal energy + kinetic energy are everywhere constant. Now since $E_T = PV$ and $E_K = Mv^2/2$

$$PV + Mv^2/2 = k$$

The product of Pressure and Volume plus 1/2 the product of Mass and the square of velocity is everywhere constant. So for flow from a large diameter pipe to a small diameter pipe within a closed system, velocity (v) increases so pressure (P) falls. Students often interpret Bernoulli's Principle to say that that fast flow "causes" low pressure. In practice, the opposite may be true since a pressure gradient must generally be present to motivate fluid flow. Continuing, and dividing both sides by volume,

$$P + dv^2/2 = k$$

Rearranging, $P = k - dv^2/2$

So, according to this typical derivation, an increase in velocity indicates a decrease in pressure.

A major problem with this derivation is that the diagram from which it follows does not show a motivation for the flow through the pipe. Absent such motivation (from a fan, pump, air tank, etc.) the flow rate is zero and all pressures are equal. So this derivation is correct only when all velocities are zero. With a fan to motivate some actual fluid flow, the upstream pressure and density become higher, thus invalidating the incompressibility assumption.

3. The Bernoulli Explanation in Practice

The Bernoulli Principle appears widely in standard textbooks as the explanation for lift.

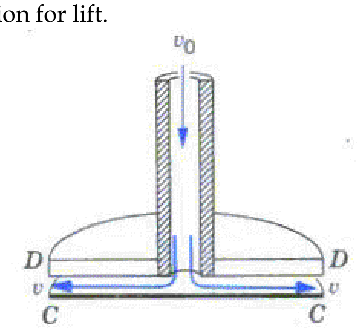

Fig. 3.1. Halliday and Resnick #HR-74-P

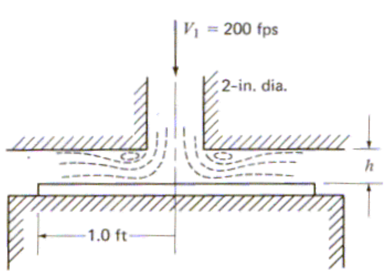

Fig. 3.2. Potter and Foss #2.32

Figures 3.1 and 3.2 are from standard college physics textbooks. The author writes Professor Halliday about figure 3.1 and receives the following "solution."

Apply Bernoulli to the top and bottom of the card, using the average velocity of the fluid and set the energy equal.

$$p_1 + dV_1^2/2 + dgy_1 = p_2 + dV_2^2/2 + dgy_2$$

Since $y_1 \sim y_2$ and $v_2 = 0$,

$$p_1 + dV_1^2/2 = p_2$$

$$p_2 - p_1 = dV_1^2/2$$

Force = pressure * area

$$F = (p_2 - p_1) * A = A * dV_1^2 / 2$$

Thus, force equals one half of the product of the area, the density and the square of the average velocity.

The author sees several problems with this "solution." In general, the flows above and below the card are not necessarily in the same flow stream. To the extent the flow expands radially, the assumptions of constant average velocity and constant density may not hold. In equation (1): First, the fluid velocity above the card is not constant; there is no particular reason to take an average velocity. Second, the fluid above the card does not flow, in a closed loop, around the bottom of the card, and back over the top of the card again. There is simply no closed-loop to link these two regions, so the claim that these two values must be equal, has no basis. Third, the fluid in the cylinder, at the center of the card has higher density than that at the open edge of the card, so the constant density assumption is invalid.

In equation (4) the equation has force proportional to the square of the velocity. As such, there is no limit to the force [F], and it can be arbitrarily large. This, in turn, implies the pressure above the card can be arbitrarily small, even negative.

4. Radial Momentum

Radial Momentum is the sum of the individual momenta of all the particles of a system, in directions away from the center of mass.

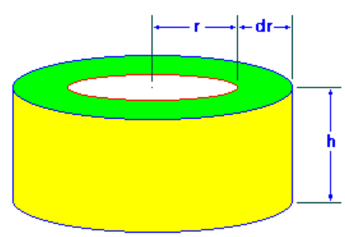

Fig. 4.1. Radially Expanding Ring of Fluid

Like linear momentum, Radial Momentum obeys conservation laws. The fragments of an explosion, or the molecules of a radially expanding fluid, once set in radial motion, tend to stay in radial motion and maintain the total Radial Momentum, until some force acts on the individual elements. Once fluid molecules start expanding radially, Radial Momentum keeps these molecules expanding into larger and larger volumes. As the fluid expands, the density and the pressure both fall and this induces lift. In Figure 4.1 as the radius [r] increases and the ring width [dr] and the ring height [h] stay constant, the volume of the fluid increases. This accompanies a reduction in density.

This paper demonstrates, with simple experiments and models that Radial Momentum, and not fluid velocity, accounts for lift or pressure drop in many systems.

5. The Levitator

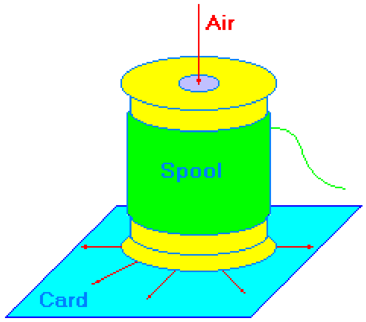

Fig. 5.1. Simple Levitator

The Levitator is a device that lifts a flat panel. In figure 5.1 the experimenter can lift a playing card by blowing air down through a spool of thread and onto a playing card. This is essentially the same device as in figures 3.1 and 3.2.

The standard explanation in textbooks and in museums is: "Bernoulli says that fast flow associates with low pressure." This is incorrect in two ways. First, Bernoulli does not say that and second, fast flow does not account for lift.

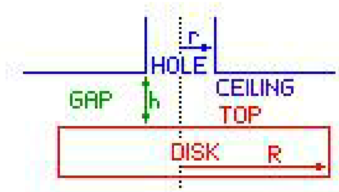

Fig. 5.2. Schematic of the Levitator

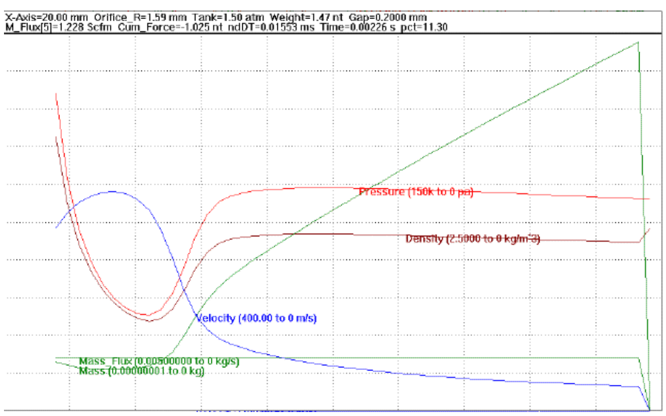

Fig. 5.3. Computer Simulation of the Levitator

Figure 5.3 shows a computer simulation of the operation of the levitator using Radial Momentum. It shows various variables as they develop from the center hole toward the outer edge of the disk.

A pump motivates the flow of air down the hole. The pressure (red) is therefore greatest at the center of the levitator, at the left of Figure 5.3. As the air enters the gap between the ceiling and the top of the disk, it begins its journey toward the outer edge of the disk. As the air continues this journey, the momentum of the molecules plays an important role.

As a ring of air enters larger and larger rings, its density (brown) and its pressure (red) both decrease. This decreasing pressure sets up a pressure gradient that motivates an additional acceleration of the air molecules and further increases the velocity in a positive feedback cycle. As the air continues to expand, its density and pressure continue to fall, eventually falling below the ambient pressure beneath the card. The low pressure in this "active region" accounts for all the lift. Indeed, in experiments with water as the fluid, the active region appears as a white cavitation ring around the central hole as the low pressure in the active region draws tiny air bubbles out of the water. See figure 5.4.

Two forces oppose the radial expansion of the air. First, friction converts some of the energy to heat. This appears as a bifurcation of the pressure and density curves. Second, back-pressure from the ambient air at the outer edge of the disk provides a net positive pressure slope against which the air must climb.

Just as the initially emerging air experiences positive feedback that increases its velocity, another self-reinforcing mechanism appears at the end of the active region. As pressure starts to rise against ambient pressure and lower-momentum air ahead, it experiences additional deceleration. This, in turn, further reduces velocity. This positive feedback cycle induces a rapid rise in pressure or "hydraulic jump." After the jump, the pressure decreases gradually toward the outer edge of the disk, per normal gradient flow.

The active region and the hydraulic jump are also evident on the back of a dinner plate under a stream of water. See figure 5.5.

Fig. 5.4. Cavitation Ring

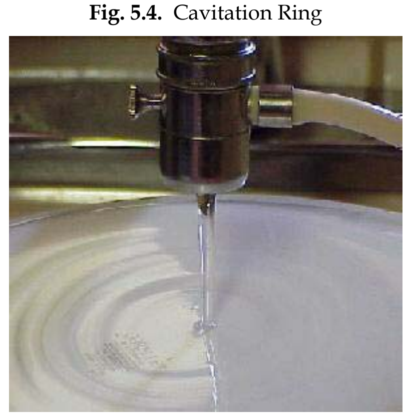

Fig. 5.5. Stream of Water on a Dinner Plate

6. Experiments with Channels

To further test the hypothesis that Radial Momentum, not fluid velocity, as an explanation for lift, the author constructs a levitator table and tests it against a series of disks with different air channels.

Fig. 6.1. Levitator Table

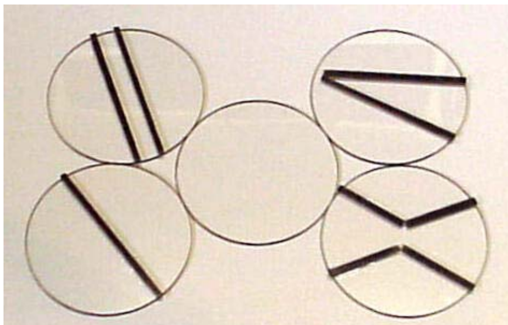

Fig. 6.2. Levitator Disks with Air Channels

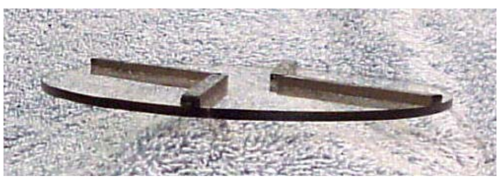

Fig. 6.3. Detail of "Hourglass" Channel

The author tests each of the disks in figure 6.2 by holding them beneath the levitator table in figure 6.1. All of them cling to the bottom of the table except the one with a parallel channel. The disk with the parallel channel is the only one that restricts the flow so that it is linear, not radial.

7. Tube and Cone Experiment

To further test the hypothesis that Radial Momentum, not fluid velocity, is an explanation for lift, the author constructs a tube and cone experiment.

The cone in figure 7.1 (that allows for Radial Momentum) collapses whereas the tube in figure 7.2 (that does not allow for Radial Momentum) does not collapse.

If fluid velocity were an explanation for lift, garden hoses would flatten out whenever gardeners turn on the hose faucets.

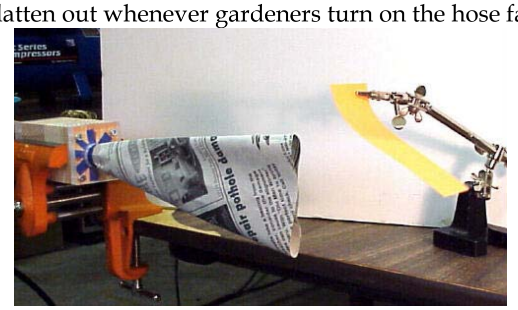

Fig. 7.1 Paper Cone

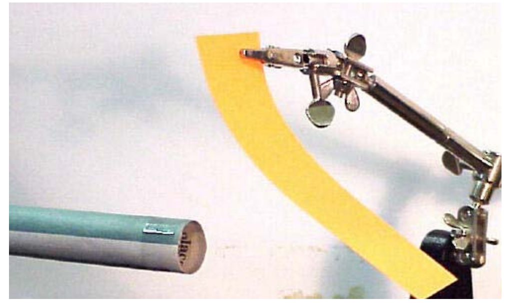

Fig. 7.2. Paper Tube

8. Hand-Out-The-Car-Window Experiment

The author encourages numerous researchers to stick their hands out the car window while they are riding along to observe the effects of shape and angle of attack on lift. Note: none of the researchers is wearing a white lab coat, carrying a clipboard or confronting the ethical dilemmas associating with receiving research grants. They all report that lift is entirely a function of angle of attack and that shaping the hand so as to introduce curvature has no effect.

9. Business Card Levitation Experiment

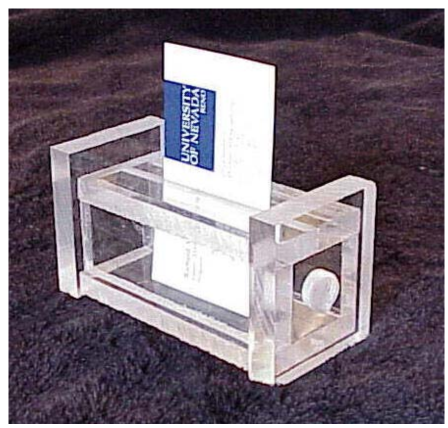

Fig. 9.1. Business Card Levitator

A Professor of Fluid Dynamics at the University of Nevada (who administers a graduation exam that includes using velocity to calculate the lift of a levitator) challenges the author to build a levitator that entrains linear flow. He claims it should work every bit as well as a levitator that allows for radial flow.

The author constructs such a device with a design to lift the business card of the professor. See figure 9.1. The device fails to lift the card, further confirming the hypothesis that Radial Momentum, not fluid velocity, attends lift.

Conclusions

This paper demonstrates that Radial Momentum, not fluid velocity, explains lift.

References

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[3] Halliday and Resnick, **Fundamentals of Physics** 3rd ed. (1988).

[4] Potter and Foss, **Fluid Mechanics** (1975).