PUMP CONSULTING & TRAINING LLC
Joseph R. Askew
1811 Stonecrest Ct.
Lakeland, Fl. 33813
863-644-3118-Office Phone
863-899-9896-Cell Phone
E-mail: pmpcnslt@tampabay.rr.com
"Objectivity in pump selection, systems, troubleshooting & training "

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Presentation Topic: "How Centrifugal Pumps Pump & Airplanes Fly"
Presenters Name: Joseph R. Askew
Company Name: Pump Consulting & Training LLC

Abstract:

The Conservation of Energy Law is fundamental to many aspects of science and engineering. Daniel Bernoulli was an 18th century Dutch/Swiss mathematician that formulated and applied this Conservation of Energy Law to fluid mechanics into what we know today as the Bernoulli Principle or Bernoulli's Law. This paper will investigate how Bernoulli's Law is the basis for how centrifugal pumps pump and airplanes fly.

Respectively submitted:
Joseph R. Askew
Pump Consulting & Training LLC
1811 Stonecrest Court
Lakeland, Fla. 33813
Office Phone: 863-644-3118
Cell: 863-899-9896
Email-pmpcnslt@tampabay.rr.com

"Objectivity in pump selection, systems, trouble-shooting, & training"

"How Centrifugal Pumps Pump & Airplanes Fly"

One of the same scientific principles that help us to explain how centrifugal pumps function may also help us to understand how airplanes fly. We will endeavor to explore those concepts during this discussion and see how they apply to our pumps, planes, and maybe some other common devices that we see in our industrial and everyday lives.

Let us begin by laying a little groundwork to gain some insights into our principles of interest. The Conservation of Energy Law is fundamental to many aspects of science and engineering. This law states that energy cannot be created or destroyed. We can only transform energy from one form into another form.

Thermodynamics is the branch of science that describes the properties of a fluid. One of the principle results of the study of thermodynamics is the Conservation of Energy.

Daniel Bernoulli was an 18th century Dutch/Swiss mathematician that formulated and applied this Conservation of Energy Law of fluid mechanics into what we know today as the Bernoulli effect following the Bernoulli Principle or Bernoulli's Law.

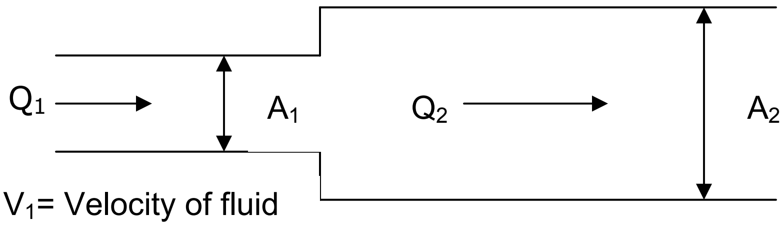
For the study of pumps and pumping systems we refer to the energy within a pump or pumping system as its "Head" energy. Head energy is that energy contained in that fluid per pound or unit mass. In general, a liquid may have three kinds of head energy, or stated another way, the capacity to do work may be due to three forms of energy:

Potential Head Energy – Defined as that work that can be done or is possible from a liquid falling from a vertical distance. We will designate our potential head energy component as 'Z', which is usually determined by a height distance above or below our system in question.

Static Pressure Head Energy – Defined as an equivalent height to which a liquid can be raised by a given pressure. To stay in context with the concept of "Head", pressure head energy units are normally converted to equivalent heights to which a liquid could be raised by that pressure. We will designate our pressure head energy component as 'P' = [PSI x 2.31]/ s.g. where PSI is the pounds per square inch of pressure and s.g. is the fluid's specific gravity.

Velocity Head Energy – Defined as the vertical distance a liquid would have to fall to acquire the velocity "V". By definition velocity head = $V^2/2g$. This definition comes from the Law of a Falling Body which states that when the height of a body falling to earth is known, we can theoretically predict what it's terminal velocity, of course neglecting good old air resistance for this discussion, will be upon hitting the earth. Conversely, knowing the velocity of a body as it exits upward we can theoretically determine to what height or head it will travel or how much work the fluid can do.
$H= V^2/2g$ where:
H = Height of falling body, or head in feet, to attain 'V' equivalent to our velocity head.
V = Velocity of moving or falling body from height 'H', in feet per second.
g = Acceleration due to gravity ($\simeq$ 32.2 feet/second^2).

Allow us to further elaborate how velocity is determined to help understand how all this comes together.
By definition: flow is defined as Q = V x A. Where:
Q = Flow value of our fluid flowing through cross sectional A @ Velocity V.
V = Velocity of fluid through the cross sectional area A.
A = Cross Sectional Area through which the fluid flows.
From this definition we can see in Figure #1 that if we hold our fluid flow Q constant and increase the cross sectional area from area 1 (A_1) to area 2 (A_2) through which the fluid flows, then the fluid velocity V must decrease as will the fluid velocity head energy $V^2/2g$. Conversely, if we reduce the cross sectional area through which the fluid flows then the fluid velocity V must increase as will the fluid velocity head energy $V^2/2g$.



V_1= Velocity of fluid flow Q_1 in area A_1

V_2= Velocity of fluid flow Q_2 in area A_2

For Constant Flow: $Q_1 = Q_2$

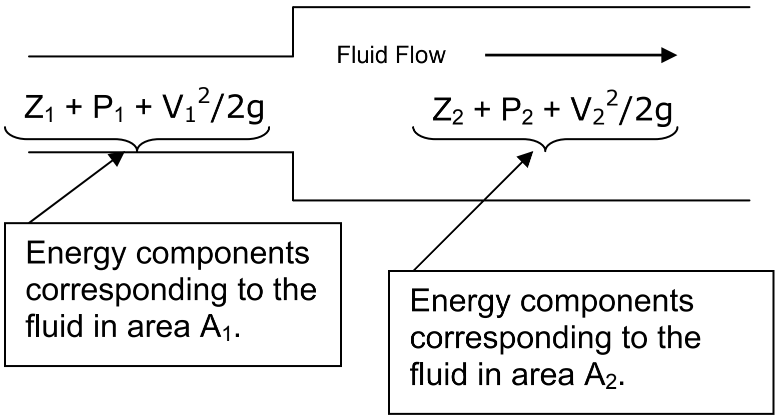
$Q_1 = V_1 \times A_1$
$Q_2 = V_2 \times A_2$
For Constant Flow: $Q_1 = Q_2$
Therefore:
$V_1 \times A_1 = V_2 \times A_2$
Given that A_2 is > A_1
then $V_2 < V_1$
As area increases, velocity decreases for constant flow. As area decreases, velocity increases for constant flow.

Figure #1 – Example of velocity, V, changes with constant flow, Q, with change in the cross sectional area through which the fluid flows. As area increases, velocity decreases for constant flow. As area decreases, velocity increases for constant flow.

The total sum of all the energies at any given point in a pumping system is comprised of our three types of energy.

Total Head Energy = Potential Head Energy (Z) +
Static Pressure Head Energy (P) + Velocity Head Energy ($V^2/2g$).
Or stated as: Head = $Z + P + V^2/2g$. At any given point in our pumping system we will have these three energy forms.

Since our Law of Conservation of Energy states that energy cannot be created or destroyed but only converted from one form to another, we can expand Figure #1 to include our 3 energy forms to further our discussion. In keeping with the laws of Thermodynamics and conservation of energy, Bernoulli's Principle states that the sum of all forms of energy in a fluid flowing along a streamline is the same at any two points in that path. Therefore $Z_1 + P_1 + V_1^2/2g = Z_2 + P_2 + V_2^2/2g$ as seen in Figure #2.



Energy Components corresponding to the fluid flowing from A_1 to A_2
<u>Z = Potential Head Energy</u>
<u>P = Pressure Head Energy</u>
<u>$V^2/2g$ = Velocity Head Energy</u>

<u>Figure #2</u> – Bernoulli's Principle states that the sum of all forms of energy in a fluid flowing along a streamline is the same at any two points in that path. Therefore $Z_1 + P_1 + V_1^2/2g = Z_2 + P_2 + V_2^2/2g$.

For all practical purposes, our fluids potential energy component (Z) is the same for area A_1 as it is for area A_2. In the big scheme of things there is very little to no difference in the vertical distance of our fluid flowing in our example. Therefore we can say that $Z_1=Z_2$. From this conclusion we can simplify our Bernoulli's Equation to read:

$$P_1 + V_1^2/2g = P_2 + V_2^2/2g$$

From this we can see that for our fluid flowing from area A_1 to area A_2 that our conservation of energy will be limited to energy changes in our pressure head energy and velocity head energy only. From Figure #1 we determined that the fluid velocity changed inversely as the area changed and thus the Velocity Head Energy component also changed accordingly. From this we can see that area 2 <u>increased</u> from area 1, with a corresponding <u>decrease</u> in velocity and Velocity Head Energy. Therefore if we are to comply with Bernoulli's Principle and the Law of Conservation of Energy and if our Velocity Head Energy ($V^2/2g$) <u>decreases</u>, then our Pressure Head Energy (P) must <u>increase</u>.

In keeping with the laws of Thermodynamics and conservation of energy, Bernoulli's Principle states that in an ideal fluid a decrease in velocity will simultaneously result with increase in pressure. And visa versa that an increase in velocity will simultaneously yield a decrease in pressure. We know this today as the Bernoulli effect.

This is enough background information for me. I trust it is for you. Now, let's see how our Bernoulli's Principle and the Law of Conservation of Energy explains how centrifugal pumps pump & airplanes fly.

How Centrifugal Pumps Pump - Centrifugal Pumps Are Velocity Machines

A centrifugal pump is essentially a velocity machine. The pump's impeller is a rotating piece of equipment that increases the fluid velocity within the confines of a pump housing or pump casing. As we can see in Figures #3-#6, the pump impeller rotates at some speed, determined by the input driver speed, and passes this velocity energy to the fluid within the pump.

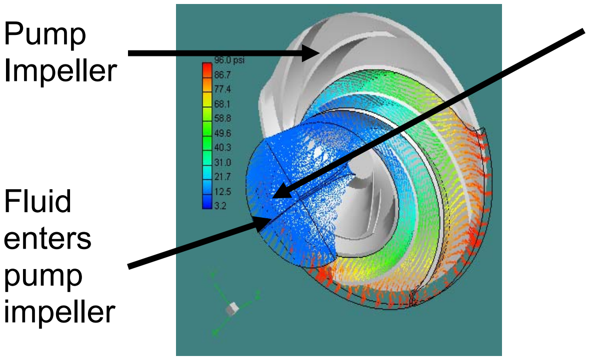


Figure #3
Fluid enters the inlet of a centrifugal pump impeller with some entrance velocity as determined by the suction system. As fluid enters the pump impeller it is captured by the rotating impeller vanes and begins to add velocity to the fluid.

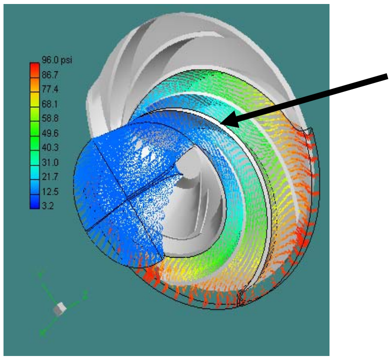


Figure #4
The fluid is captured within the impeller/pump housing, and continues to increase the fluids velocity corresponding to the increasing peripheral velocity of the impeller.

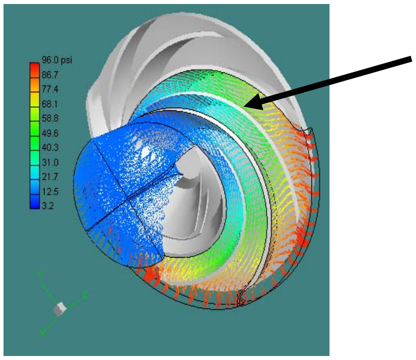


Figure #5
The impeller outer velocity increases with the gradual increase of its diameter. As the fluid continues through the impeller, the fluid velocity also increases with the gradual increase of the pump impeller diameter and the pump impeller velocity.

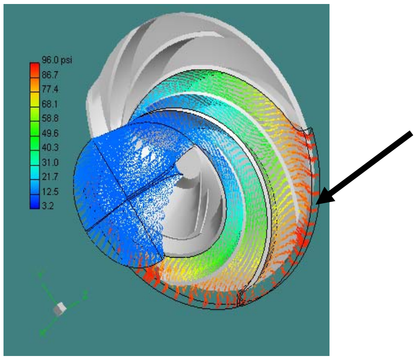
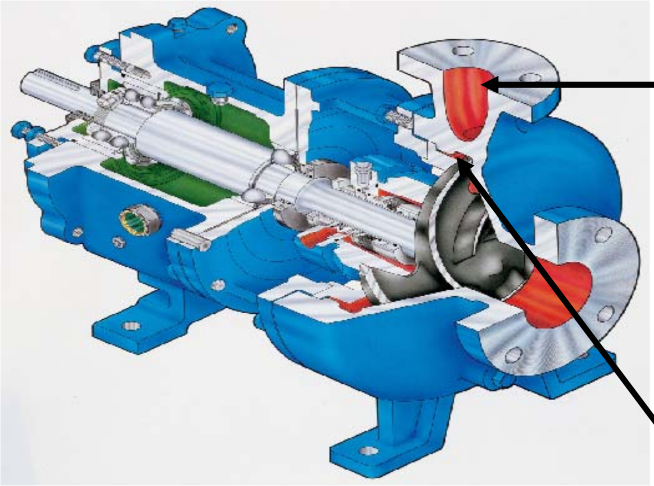


Figure #6
The fluid reaches its maximum velocity as the fluid reaches the pump impeller's outer diameter. At this point all of the increased velocity energy available from the rotating impeller has been imparted to the fluid. We have increased the velocity head energy of the fluid due to the increased fluid velocity.

It is at this point in Figure #6 that our centrifugal pump has pretty much done its job. We are finished converting the mechanical rotating work energy to our fluid when the impeller has added all of its available velocity to the fluid. Our fluid has more energy now than it did upon entering the impeller. We have increased the fluid velocity head energy due to the increased fluid velocity. The ($V^2/2g$) velocity head component of the total energy equation has now been increased.

Figure # 7 illustrates that the next step for our fluid is to exit the pump and travel into the system piping. It is at this point that our fluid will go from a relative confined space inside the pump, smaller area with relative high velocity, to a region of increased area resulting in a decreased velocity. The decreased fluid velocity will decrease our ($V^2/2g$) velocity head component of the total energy equation. However, from our conservation of energy discussions we know that energy cannot be created or destroyed. With the reduced velocity in the piping our velocity head component of our total fluid energy has decreased upon exiting our pump, which means some other energy component must increase to comply with our energy conservation. For all practical purposes, as the fluid exits the pump impeller into a lower velocity zone we have little to no change in the fluid's static elevation difference. This means that our potential static head energy component is essentially unchanged immediately upon exiting the pump. Therefore, to maintain our conservation of energy with the reduced velocity head upon exiting the pump, and potential static head relatively unchanged, then the only other energy component we have is the pressure component. It is at this point in our pumping system that the velocity head energy is transformed into pressure head energy that can be seen on a pressure gauge in the form of increased pressure. This is how a centrifugal pump pumps. Its energy is added to the fluid by way of increased velocity & thus Velocity Head energy that is converted to Pressure Head energy as the fluid exits the pump. A centrifugal pump does not generate or add pressure per se but rather adds velocity head. This distinction must be made to differentiate a centrifugal pump from a positive displacement type pump, which in fact does impart its energy by adding pressure to the fluid as opposed to adding velocity. Recognize that, as the fluid leaves our centrifugal pump we still have a fluid velocity going into our system so not all of the increased velocity head energy imparted by our centrifugal pump impeller will be transformed into pressure head energy. Some of the total system energy will still be in the form of a velocity head energy component. That is why simply looking at pressure gauge readings will not tell you the total pump head story. We still must consider the velocity head components in the fluid.



As the fluid exits the pump, the cross sectional area increases, the fluid velocity decreases thus decreasing the Velocity Head energy ($V^2/2g$). With the reduced ($V^2/2g$) the law of conservation of energy states that the Pressure Head energy must increase.

Fluid Velocity & Velocity Head energy ($V^2/2g$) has been increased to it's maximum at the impeller tip.

Figure #7 – Fluid Velocity & Velocity Head energy ($V^2/2g$) has been increased to it's maximum at the impeller tip. As the fluid exits the pump volute the cross sectional area increases thus decreasing the already added velocity head energy. Conservation of energy law dictates that velocity head energy must have been converted to some other energy type. Since our potential static energy component is unchanged for all practical purposes, the only energy component that could have been changed is the pressure head energy. As the fluid exits the pump our pressure head energy increases as the velocity head energy decreases.
"Photo courtesy of Goulds Pumps, ITT Corporation"

A centrifugal pump is a velocity machine that increases the fluid velocity and thus the velocity head energy, which is converted to pressure head energy upon leaving the pump. This is our centrifugal pumps example of the

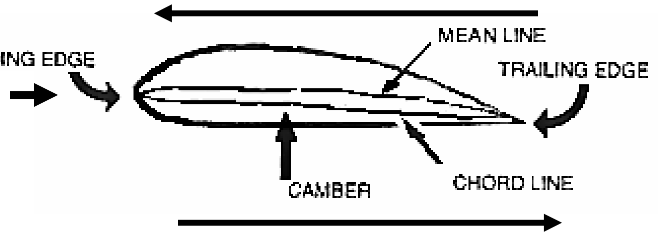
Bernoulli effect. Now let’s see other everyday items that can be explained by Bernoulli.

How Airplanes Fly

I spend much of the year conducting pump courses throughout the USA. Sitting in an airplane on an airport runway about to take off, I am still amazed that this very heavy object full of passengers, luggage, fuel, etc. is actually able to leave mother earth and fly! How does it do that?

Airplane wings are made in a quite unique and specific shape known as an airfoil design that generally is wider/taller on its upper surface than on its lower surface. This shape is to provide primarily lift as well as to reduce frictional drag on the wings.

Cross-section of an Airfoil airplane wing traveling in this direction.

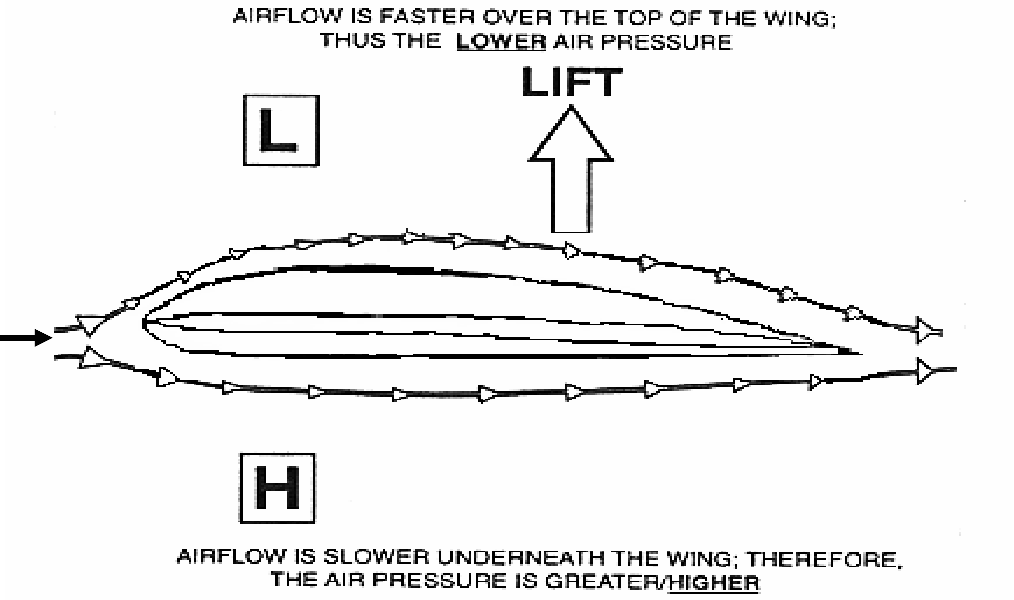


Airflow Q hitting the leading edge of our airfoil airplane wing.

Airflow velocity in this direction.

Figure #8 – Depicts a classic airfoil airplane wing shape cross-sectional. Note: the curved upper surface is wider/taller than its lower surface.

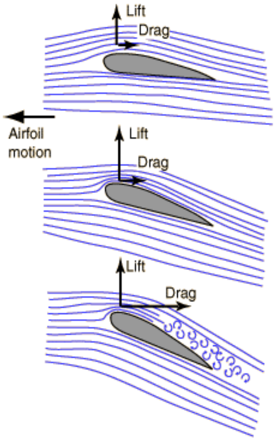
As our airfoil wing or airplane wing and airplane begin to travel down the runway from right to left on our paper, the air will begin to flow over the wing from left to right on our paper. See Figure #8. Theoretically, the airflow Q hitting the airfoil’s leading edge will be equally split along the top path and bottom paths of the winged airfoil. The equally split airflow will flow over and under the wing until they rejoin at the trailing edge. The distance the airflow must travel along the top of the airfoil is longer than the distance the equal airflow must travel along the bottom of the airfoil. The only way for the two equal air streams to meet at the trailing edge is for the airflow along the top of the wing to be traveling faster, higher velocity, than the airflow along the bottom of the wing. Another way to consider the dynamics of our split airflows is to consider that due to the wider/taller shape at the top of the airfoil that the air flowing over the top is being squeezed into a smaller area. This reduced area on the top of the airfoil/wing will generate higher velocity airflow as compared to the airflow over the bottom of the airfoil/wing. In any case, our airflow along the top of the airfoil/wing will see an increased velocity as compared to the velocity of the airflow along the bottom of the airfoil/wing. Getting back to our previous discussion about the laws of Thermodynamics, conservation of energy, and Bernoulli's Principle we know that an increase in velocity will simultaneously result with a decrease in pressure. This means that since we have increased the velocity of our airflow along the top of our wing that we have reduced the pressure along the top of our wing. With reduced pressure along the top of our wing then we have liftoff and our airplane will fly. See Figure #9 & 10.



Airflow is split ½ to top and bottom of wing.

Figure # 9 –Airfoil/wing allows us to fly in our airplanes.

Airfoil



The air across the top of a conventional airfoil experiences constricted flow lines and increased air speed relative to the wing. This causes a decrease in pressure on the top according to the Bernoulli equation and provides a lift force.

Figure # 10 – The Conservation of Energy, and Bernoulli's Principle states that an increase in velocity will simultaneously result with decrease in pressure. Increased airflow velocity along the top of our wing gives us reduced pressure along the top of our wing resulting in liftoff and our airplane will fly.

There are many other examples in our industrial and personal lives where the Bernoulli effect has been applied. Some of these include throwing a curve on a baseball, venturi meters, steam jet ejectors, eductor pumps, fertilizer sprayers, and swimming pool leaf baggers to name but a few. All of these products utilize a high velocity fluid medium that creates a low-pressure zone to move an object, suck some other fluid or material into its stream, or mix one fluid with another fluid. They all use the Bernoulli effect to perform some task to help us in our everyday lives.

Conclusion

The Law of Conservation of Energy adapted by Bernoulli for flowing fluids gives us today what we know as the Bernoulli effect. The flow region where the fluid velocity increases will give us a decrease in pressure. In the high velocity flow through a restriction or area reduction, kinetic velocity head energy must increase at the expense of pressure energy. Conversely where the fluid velocity is decreased due to an increased flow area, we must have a corresponding increase in pressure. We have many items in our everyday lives that behave according to the Bernoulli effect. Centrifugal pumps are certainly a prime example of this principle at its best. Flying in airplanes now is a little more reassuring that we have good hard scientific explanations for why those big heavy birds can leave mother earth and take us with them.

I wish you successful pump ghost hunting.

Joseph R. Askew – “The Pump Ghost-Hunter”
Pump Consulting & Training LLC
1811 Stonecrest Court
Lakeland, Fla. 33813
Phone: 863-644-3118
Cell: 863-660-0642
pmpcnslt@tampabay.rr.com

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