Thinking About Vacuum

Triton® White Paper

Ever wonder how they pick up a bowling ball with a small vacuum cleaner in TV commercials? Ever wonder why that pebble rattles around in the end of your hose when you try to vacuum your car mats? Ever wonder how "inches of mercury (" Hg)" or "cubic feet per minute (cfm) of airflow" affects the job you're trying to do? We'll explore those issues briefly in this white paper.

Three main factors are important when thinking about how powerful the suction a vacuum pump can create. These factors are vertical lift (as expressed in units like inches of mercury); airflow (as expressed in units like cfm or miles per hour); and frictional losses. And as we discuss each of these three factors, let's think about what is actually happening when you "vacuum"….and how the vacuum is different when you're moving a liquid product, like sucking your milkshake through a straw, versus a solid product, like vacuuming dirt from your carpets.

Vertical lift

At sea level, Mother Nature exerts a pressure of 14.7 psi all around us. Air has weight, and as the 17th century Italian scientist Evangelista Torricelli said, "we live submerged at the bottom of an ocean of the element air". Torricelli went on to develop the mercury barometer which is still used to measure atmospheric pressure.

When you are drinking your milk shake out of a straw, you are actually removing air by creating a partial vacuum in your mouth. The liquid is pushed up the straw by the weight of "ocean" of air - atmospheric pressure - in the cup….so technically, instead of "sucking" it in, the air pressure is actually "pushing" it toward you and the lower air pressure in your mouth. (Or consider a siphon, in which liquid flows from a higher reservoir, up through a short leg, down through a longer, heavier leg, and into a lower reservoir. The siphon is started by creating a partial vacuum, but then the weight of the fluid in the longer, heavier leg creates lower "hydrostatic pressure" than the atmospheric pressure, allowing the fluid to continue to flow. But once the vacuum is reduced, the siphon effect is lost.)

In a perfect vacuum, all 14.7 psi of air pressure is gone…all of the air molecules are removed, leaving no pressure or weight. By definition, then, that limits the amount of vacuum that can be created….you can't take away more than is there. A perfect vacuum will lift 29.92" of mercury (Hg), but cannot be achieved in the real world. In fact, as you go past 24" to 26" Hg or more, it becomes exponentially more difficult to continue to increase vacuum…..and the remaining air expands, making it harder to remove the few molecules that remain.

Triton machines put up >26" of Hg. (The T500 system has vacuum relief set at 18" Hg.) But what does this mean in terms of a product we can understand? In a simple analysis, mercury is 13.5 times heavier than water, which weighs 8.3 lbs/gal. A vacuum of 26" Hg would then lift (13.5 x 26) 351 inches (29 feet) of water as a solid column. Even a perfect vacuum would only lift water ~33 feet. It is not possible in nature to lift a solid column more than that...and if you've got something that is heavier, e.g., a sludge that weighs 17.5 lbs/gal, then the height it can be lifted is less. In this example, mercury would only be ~6.5 times heavier than the sludge….meaning that 24" Hg is the same vacuum level as 156" of 17.5 lb/gal sludge, which is 13 feet. That means you'll only get about 13 feet trying to lift a solid column of sludge of that weight. (The secret to a higher lift is to introduce air….to "blow" the product up. We've seen lifts of up to 60-100 feet or more using this method…more on it later.)

While we're on this subject, let's consider the case of the bowling ball held up by a small vacuum cleaner. Those vacuum cleaners might put up 6" Hg, which is equivalent to ~81 inches of water. One cubic inch of water weighs 0.036 pounds, or 3.6 pounds for 100 cubic inches (you may remember that water weighs 8.3 lbs/gal, and contains 231 cubic inches…8.3 divided by 231 = 0.036). By calculation, we can determine that 81" of water would exert a pressure of ~2.9 pounds per square inch on the bowling ball. The catch is, the advertisers greatly increase the square inches by using an inverted funnel on the end of the vacuum hose where it meets the ball. (And since the ball is spherical, it has 3 times as much surface area as a flat surface would). If the vacuum is applied against an area of 20 square inches, then the force supporting the ball is 2.9 x 20 = 58 lbs, and a typical bowling ball weighs 16 lbs, so the job is easy….and misleading. Because a vacuum can support a bowling ball (or a man, or an elephant, given enough surface area) doesn't mean it cleans better or can convey further.

You can also see why properly sealed joints and fittings, particularly on the suction side, are necessary for most efficient vacuuming and conveying….a little leak can dramatically reduce the amount of vacuum created. If the bowling ball wasn't well sealed against the funnel, it would drop right off. Or think about when you're sitting in your dentist chair, and the hygienist asks you to close your mouth around the suction tube…it instantly creates the vacuum and improves the "suction".

Airflow

Airflow is obviously the amount of air that passes through the system. But there are at least a couple of ways that airflow impacts the effectiveness of the system. The first is the volume of air that moves; the second is the speed of that air. In the U.S., we typically measure the volume of air in units of cubic feet per minute (cfm), and typically measure the speed of the air in feet per minute (fpm) or miles per hours (mph).

The volume of air moved is important in different ways, depending on whether you are moving a column of liquid, or whether you're trying to vacuum a solid. Let's look at the first case, and assume that for example you intend to empty a tank of light oil into a vacuum box by vacuuming through the box. As you start the vacuum machine, it first has to empty the air that is in the lines and in the vacuum box, before it starts moving product. How long it takes to evacuate depends on the volume of air that the system can move. A higher cfm machine will get the job "started" faster. But in many cases, the time is takes to empty the air and start vacuuming product is pretty small compared to the length of the overall job, so it may not be a factor.

Let's think for a minute about what happens once the air is displaced or gone from the system. At that point, the vacuum has created a lower air pressure in the suction hose leaving the tank, and normal atmospheric pressure is still covering the tank like "an ocean of the element air", so the product is pushed to the lower pressure, which carries it into the vacuum box. When the product fills up the hoses and is pulled (pushed!) into the vacuum box, air is no longer flowing – it is a vacuum! So the airflow becomes immaterial.

Contrast that with a situation where you are trying to "vacuum" a dry product, say for example, corn kernels out of a barge. In this case, you don't actually create a vacuum….any air that is removed from the system is immediately replaced by new air entering with the product. In the light oil example, we were lifting a "solid column" of oil which for most practical purposes keeps air out of the system, maintaining the vacuum. (We'll ignore concepts like vapor pressure in this discussion, but it is possible to pull too strongly – for example, extracting water from product and contaminating the oil in a rotary vane pump.) In the corn case, the air is being used to "blow" the corn through the lines and catch it in a container. Since the corn has weight, it needs both enough volume (cfm) and airspeed (fpm) to convey it.

Airspeed is determined by the amount of volume through the particular geometry of the lines. For the same volume of air, it will move slower through a large line than through a small one. Imagine trying to blow the same volume of air through a straw, or through a garden hose….you'd definitely be able to tell the difference in speed at the output.

Calculating the airspeed at the entrance of the pump requires some simple geometry. Let's assume that it's a Triton 1500 machine with a pump that pulls 1600 cfm of air volume. To convert from a volume airflow in cubic feet per minute to airspeed in feet per minute, you have to know what size the opening is that the air goes through. Let's assume that it is a 4" inlet to the pump. We'll need to determine the cross-sectional area of the opening….which is actually easier than it sounds. The area of a circle is πr^2. The constant π (pi) is approximately equal to 3. The radius, r, is equal to half the diameter. To square it, you simply multiply it by itself. Since we have a 4" diameter inlet, the radius is 2". To square it is 2" x 2", which brings us to 4 square inches. Multiplying by π brings us to approximately 12 square inches, or 0.084 square feet (since there are 144 square inches (12" x 12") in one square foot). That means that a 4" diameter inlet has an opening of ~12 square inches, or 0.084 square feet. To convert from 1600 cfm, we divide by 0.084 square feet and find that we have an airspeed of 19,048 feet per minute through a 4" inlet.

Once you have feet per minute, it is easy to convert to miles per hour by multiplying by a factor of 0.0114. In this case, 19,048 feet per minute is ~217 mph.

So one 4" hose has an area of 12 square inches, and two 4" hoses have double that, or 24 square inches. What many people don't realize is that two 4" hoses have less cross-sectional area than one 6" hose. Work it out (a 6" hose has a 3" radius, which squared is 9 square inches, x 3 for π equals 27 square inches, vs 24 square inches for the two 4" hoses).

Instead of having to calculate it, here is a table that shows mph for several Triton system/orifice size combinations. (Note that the Triton 500 system actually puts up 430 cfm, and the Triton 1500 systems puts up 1600 cfm).

Theoretical airspeed in mph, without frictional losses:

cfm	2"	3"	4"	5"	6"	8"
500	233	103	58	37	26	15
1500	866	385	216	139	96	54
2000	1082	481	271	173	120	68
2500	1353	601	338	216	150	85

Now, there is a practical limitation on the airspeed through an orifice…..it is not possible in real life to achieve speeds approaching 1000 mph or more that we show for the 2" orifice (an issue called "sonic velocity").

But what if instead of 866 mph put up by a 1500 cfm machine through a single 2" inlet, you doubled the inlet and had two 2" openings? The answer is that you would cut the airspeed in half…dropping to 433 mph through each opening. So you see that it is possible e.g., to install a tee on a hose and have two or possibly three working ends, provided that each has enough airflow and airspeed.

For dry products such as grain, a rule of thumb is that there has to be at least 90 mph of air speed to properly convey. For water (not in a solid column, but say, for instance, as puddles), the rule of thumb is 60 mph. The heavier the product, the more airflow is needed.

So now to one of the original questions we posed…why does that pebble rattle around in the end of your vacuum wand when you vacuum your car mats? The wand has a different geometry than the hose itself. It is designed to have a smaller opening, which increases the air speed, and allows dirt to be picked up further away from the hose. It may pick up that pebble, but as the hose opens ups, the airspeed drops, and there may not be enough air speed to continue conveying the pebble down the line…thus is hangs up in the wand, and rattles around.

In practical application, the hose being worked may also be buried in the product, which prevents adequate airflow. In those cases, a way to improve conveying rates is by having secondary air openings at the intake nozzle. This allows air to move through the line while the hose end may be submerged. Alternatively, the hose end can be pulled out of the product on a regular basis, allowing it to "gulp" air.

So if we have an airspeed of >90 mph at the inlet to the pump, we should be able to convey solids, right? Not exactly. It should be remembered that this airspeed is at the inlet to the pump. The airspeed at the working end of the hose is quite different….possibly half as much or less…due to frictional losses.

Frictional Losses

When the product flows through the system, there is a loss of pressure caused by the rubbing of the product along the walls of the hose and fittings, and the turbulence of the product. This is called “friction loss”. Friction loss is thus a resistance to flow due to the length, diameter, flow, and type of hose or pipe; the characteristics of the product, such as viscosity; and the flow rate. The use of rigid pipes with a smooth interior can result in 50% greater conveying rates than flexible hoses with corrugated interiors. However, the flexible hoses are often more convenient to use. Increasing the intake hose length decreases the conveying rate because there are more frictional losses due to the longer hose. Additionally, putting a bend in a hose greatly increases frictional losses. The use of slow radius turns and flat horizontal runs minimizes the frictional losses, but frictional losses still might be responsible for a 50% drop from theoretical rates.

Some rules of thumb about friction loss:

- A small change in hose size drastically changes the friction loss at a given flow rate. The bigger a hose with the same flow rate, the smaller the friction loss, by a large margin.
- Friction loss increases more rapidly than the increase in flow. For example, if the flow rate is doubled, then the friction loss becomes roughly twice as much as it was originally. Which means that too much airspeed can be bad – causing high wear in hoses and fittings when an abrasive product is conveyed.
- The rougher the hose, the greater the friction loss.
- Friction loss is directly proportional to length. The friction loss in 200 feet of hose is double that in 100 feet of the same size and type of hose.
- Friction loss is nearly independent of pressure.

Considering friction losses is important. We have found that the Triton 1500 system with 4” intake hoses is an appropriate system for most solids conveying applications. From the table, you can see that it theoretically can put up 217 mph of airflow…but frictional losses may cut that in half. (For further information on solids conveying, see our white paper “Using the Solids Recovery Package”.)

Frictional losses are also the main thing that limits how long a horizontal run is possible under vacuum. Early in this paper, we talked about limits on vertical lift, but horizontally it’s mainly friction that governs distance - if good seals on joints and fittings are in place. A horizontal run of 400-500 feet is generally possible with the Triton systems, depending on the product being conveyed.

This paper is not intended to be definitive, but rather was produced to point out some of the complexities involved in “vacuum”, and of three key issues – vertical lift, airflow, and frictional losses. We examined some thoughts about a solid column of liquid, as well as the other extreme – a dry product. Many times, the actual application may be somewhere in the middle, which makes it a little more difficult to think about. If you have more questions about these concepts and how they might apply to your situation, please contact us.

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