VENTURI VACUUM GENERATORS

WHAT THEY ARE AND HOW TO DESIGN THEM INTO YOUR SYSTEM

INTRODUCTION

Vacuum generators are not new. They have been in existence for decades and are used for various purposes from simple evacuation to pick-up and work-holding devices. Their uses and applications are finding more and more acceptance as factories become more automated. With the spread of pneumatic automation controlled by PLC's and computers, air operated devices are involved in just about every automated operation.

Pneumatic automation offers clear advantages. Pneumatics are easy to implement, low cost, and easy to interface with electronics and mechanical technologies. Pneumatic's proven track record indicates that most design engineers are familiar with pneumatic components. Every design engineer is actually an automation engineer as well. You are into automation if the equipment you design performs one or more of the following: pulling, pushing, picking, placing, twisting, holding, inserting, blowing or evacuating.

Depending on the particular machine or piece of equipment, vacuum is used to do one or more of the above functions either as the primary force or on an accessory basis. The generation of vacuum alone is not sufficient. Complementary components such as valves, vacuum switches, sensors, manifolds and suction cups are just as important and the proper use of these within a system can yield all the advantages of pneumatic automation.

Where Is Vacuum Used?

As mentioned earlier, vacuum is used in just about every industrial sector. The following is just a partial list of applications:

- Pick & Place Machinery

- Assembly Machines
- Material Handling
- Labeling Machinery
- Printing Machinery Cassette
- Tape Machinery
- Packaging Machinery
- Lumber Handling
- Paper Industry
- Film Handling
- Vacuum Chucks
- Vacuum Draw-Down for Molds

How Is Vacuum Produced?

There are two basic ways of producing vacuum. The most widespread method is to use an electric-motor-driven, positive-displacement pump as shown in Fig. 1.

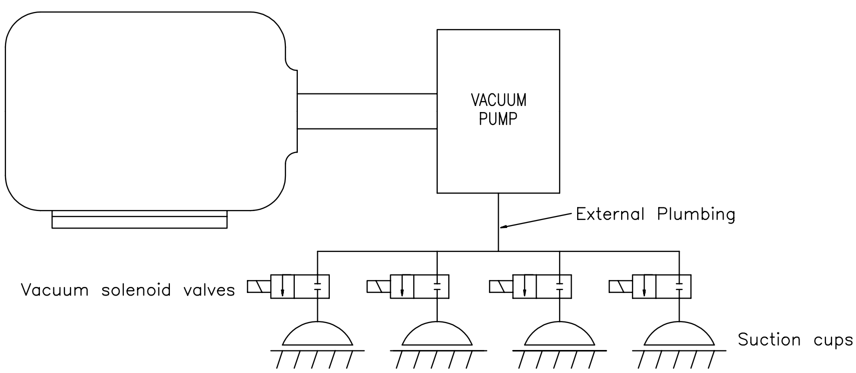


Figure 1. Typical Electric Motor Driven Vacuum Pump System

The second method of producing vacuum is by using a no-moving-part venturi, also known as vacuum generators and ejectors. As shown in Fig. 2, compressed air is allowed to flow through a nozzle which causes a venturi action. As the air expands and flows into the receiver tube, it creates a pressure lower than atmospheric pressure. This causes entrainment of the surrounding air which is more commonly referred to as vacuum flow. The entrained air, as well as the supply air, exhausts into the atmosphere.

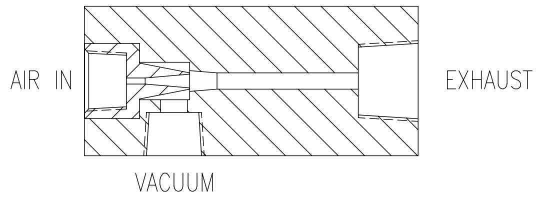


Figure 2. Compressed Air Driven Vacuum Generator

When To Use A Vacuum Pump Versus A Venturi

The application determines which one of the two methods is better suited. Though most applications can use vacuum from either one of the sources, one will clearly outweigh the other depending upon the design and application requirements from the point of view of cost, space, temperature etc.

In general the following are the advantages of using venturi vacuum generators:

- **Fast cycling**: Since there are no moving parts and the time to establish vacuum is low, venturis are ideally suited for fast cyclic applications such as pick & place, labeling, etc.

- **Temperatures**: Venturis can operate over a wide range of temperatures, especially at high temperature applications.

- **Corrosive environments**: Since venturis can be made out of a wide range of materials and there are no moving parts, they are well suited for corrosive environments.

- **Noise levels**: The only noise generated by venturis is due to air flow and can be minimized by using noise reducing mufflers.

- **Contamination**: Venturis, especially the single stage venturis, are quite insensitive to contamination. Even if particles are introduced into the device, they can be cleaned with relative ease.

- **Maintenance**: Since there are no moving parts associated with venturis, they are practically maintenance free.

- **Ease of mounting**: Since venturis are quite compact, they can be mounted very close to the work station. This makes them very attractive for integrating them as a part of the end-of-arm tooling. As this minimizes the length of vacuum line, the size can be smaller than if they were mounted at a distance.

- **Lower Cost**: Due to their simplicity, the venturis are low cost components.

When Is A Venturi Undesirable?

- One of the basic requirements of a venturi vacuum generator is compressed air. If compressed air is not available, an electric vacuum pump is the only alternative.
- If constant vacuum flow is required, venturis may not be the most efficient device compared to vacuum pumps. Also if the application requires a large vacuum flow at high vacuum, a vacuum pump may be more energy efficient than a venturi.

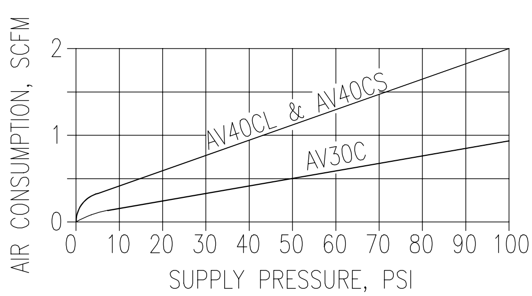
GUIDELINES FOR DESIGNING A PROPER VACUUM SYSTEM

BASIC TERMINOLOGIES

The performance of any venturi vacuum generator is defined by the following factors:

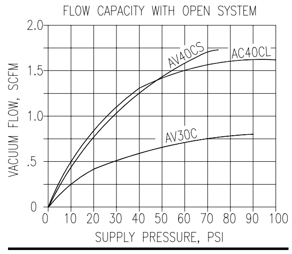
Supply Flow

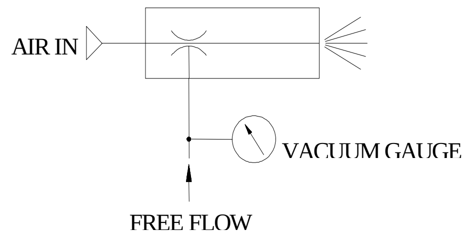
Supply flow describes the flow consumption of the device. This is usually provided by the manufacturer either as a table or a graph showing the air consumption in SCFM (**S**tandard **C**ubic **F**eet per **M**inute) at various supply pressures. They also recommend the supply pressure needed to operate the device to obtain the optimum vacuum level and flow. However, venturis can be operated at higher or lower levels than those recommended.



Flow Capacity

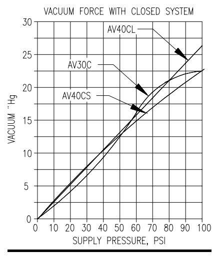
Flow capacity is a measure of free air (in SCFM) induced into the vacuum port of the device when the vacuum port is open to atmosphere. In other words the vacuum level is 0" Hg. Again this is plotted as a function of the supply pressure. This data is useful in determining the fluid flow that can be evacuated from a closed volume at atmospheric pressure.

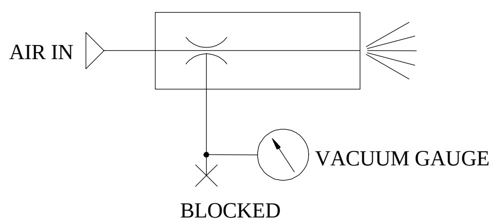

FLOW CAPACITY WITH OPEN SYSTEM
VACUUM FLOW, SCFM
SUPPLY PRESSURE, PSI
AV40CS
AC40CL
AV30C
2.0
1.5
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100


AIR IN
VACUUM GAUGE
FREE FLOW

Vacuum Level

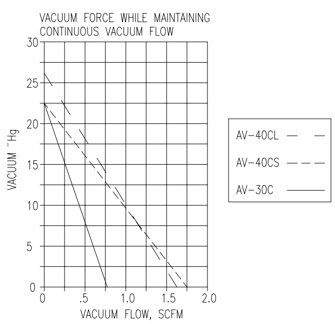
Vacuum level is a measure of the vacuum generated with the vacuum port blocked off from atmosphere. During this test the vacuum flow is zero SCFM. Vacuum level is plotted as a function of supply pressure. This data is useful in determining the force generated or weight that can be picked up by the device when picking up a non-porous load with a suction cup.

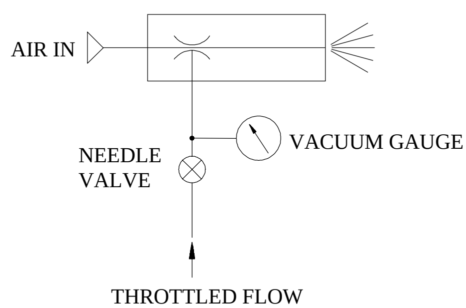




Vacuum Level vs. Vacuum Flow

This ratio shows how the vacuum level changes as the vacuum flow is throttled from fully blocked to fully open. This is normally measured with the supply pressure set at the optimum level. This data is very helpful in estimating the vacuum level when handling porous materials or when there is leakage in the system.





Evacuation Time

Evacuation time is simply the time required for a venturi to evacuate a volume from atmospheric pressure to the vacuum level of the particular venturi. The standard volume is taken as one cubic foot. For this test, the venturi is run at the pressure which creates the greatest vacuum.

DETERMINING THE SIZE OF THE VACUUM GENERATOR

Different size vacuum generators represent different power levels. Just as in an electrical system where the product of voltage and current equals the wattage level, so it is in a vacuum application where the product of pressure and volume yields the vacuum power.

Therefore the size of the venturi is determined by:

- the desired vacuum level
- the volume to be evacuated
- the time in which evacuation must be done

A Three-Step Procedure To Determine Power Requirements

Remember, it is not a pure science but a common sense approach which will help you decide which vacuum generator to use. Use the steps below to guide you.

Step 1.
Determine the overall volume in cubic feet that the vacuum generator has to evacuate each cycle. Take into account the line ID's, lengths, manifold volumes, suction cup volumes, etc. This gives you the amount of free air to be purged from the system.

Step 2.
Multiply the number from step 1 by the number of cycles per minute. The result of this is the free air to be removed in one minute (which is SCFM). Use peak requirements to be conservative. You should include a factor of safety of 2 or higher.

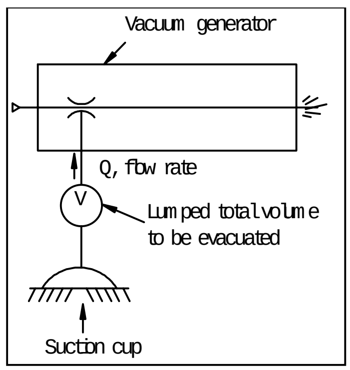
Step 3.
At this point compare flow capabilities of the different vacuum generators. Keep in mind that the vacuum flow at 0" Hg is greater than the flow at higher vacuum levels. This is especially true with some multistage venturis. Venturi vacuum flow rates drop off drastically once they go beyond 10" Hg as compared to their vacuum flow at 0" Hg. (Remember this when comparing units). For a quick and rough calculation, use the vacuum flow at 15" Hg as the average flow rate. Choose the one that meets the flow requirements based on cycle time and vacuum level required before lifting the object.

To Determine Which Generator To Use To Evacuate A Certain Volume Within A Certain Amount Of Time

The evacuation of a volume is determined by time, pressure and flow. Many units come with a chart that shows time to evacuate one cubic foot of air to different vacuum levels. These charts can be used as guides in sizing the proper vacuum generator for the application.

What follows is a mathematical derivation showing how the evacuation process works and the final formula given is an exact way to calculate the time required to evacuate a given volume using a particular vacuum generator. If you are not too crazy about math, skip the preliminary formulas but be sure to use the final formula. It works!

Time to Evacuate a Volume When Lifting Non-Porous Materials:



Applying the continuity equation:

$$-\rho \mathbf{Q} = \frac{d}{dt}(\rho \mathbf{V})$$

Where ρ is the mass density of air:

$$= \rho\frac{\partial \mathrm{V}}{\partial t} + \mathrm{V}\frac{\partial \rho}{\partial t}$$

$$= \rho\frac{\partial \mathrm{V}}{\partial t} + \mathrm{V}\left(\frac{\rho}{\mathrm{P}}\right)\frac{\partial \mathrm{P}}{\partial t}$$

The term $\frac{\partial \mathbf{V}}{\partial t}$ is the rate of change of volume **V**, with respect to time. Assuming that the entire volume is rigid, i.e. $\frac{d\mathbf{V}}{dt}$ = 0.[1] Therefore:

$$-Q = \frac{V}{P}\frac{dP}{dt}$$

$$dt = -\frac{\mathbf{V}}{\mathbf{Q}}\frac{d\mathbf{P}}{\mathbf{P}}$$

Integrating both sides of the equation with the initial condition $\mathbf{P} = \mathbf{P_o}$ at $t = 0$ gives:

$$t = \frac{\mathbf{V}}{\mathbf{Q}}\ln\frac{\mathbf{P_o}}{\mathbf{P}}$$

In the above equation $\mathbf{P_o}$ is atmospheric pressure (14.7 psia in most cases) and **P** is the final vacuum level (in psia) to be reached.

For example, say your goal is to evacuate a 1 cubic foot of volume to 20"Hg. using an AV-60 supplied with 80 psi of compressed air. From the test data, our AV-60 has a free flow rate of approximately 1.65 SCFM. Therefore,

$$\mathbf{Q} = 1.65\ \frac{\text{ft}^3}{\text{min}}$$

$$\mathbf{V} = 1.00\ \text{ft}^3$$

$$\mathbf{P_o} = 14.7\ \text{psia}$$

$$\mathbf{P} = 14.7\,\text{psia} - 20''\,\text{Hg} * 0.49\frac{\text{psi}}{''\,\text{Hg}}$$

$$= 4.9\ \text{psia}$$

$$t = \frac{1.00}{1.65}\ln\left(\frac{14.7}{4.9}\right)$$

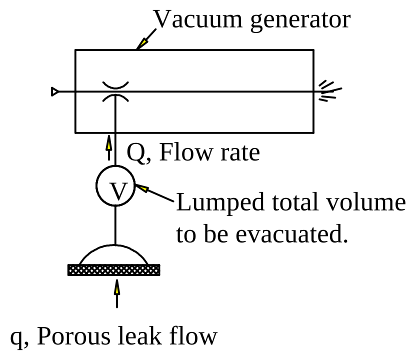
$$= 0.66\ \text{min} = 39\ \text{s}$$

If you refer to our evacuation times chart on page 8, you will see that the actual lab test results indicate that it takes 35 seconds to evacuate 1 cubic ft. of volume to 20"Hg using an AV-60 vacuum generator at 80 psi supply pressure. This is quite accurate within engineering approximations.

[1]This assumption does not take into account the flexibility of a suction cup, especially a bellows-style cup.

Time To Evacuate a Volume When Lifting Porous Materials:

Here, everything is the same except that the leak flow has to be taken into account. The final time equation is:



$$t = \frac{\mathbf{V}}{\mathbf{Q-q}} \ln \frac{\mathbf{P_o}}{\mathbf{P}}$$

Again, the leak flow **Q** will depend on the vacuum level. However, the term (**Q**-**q**) can be replaced by a factor such as .5**Q** or .4**Q** depending the porosity. As can be seen, this will increase the time to evacuate the same volume to the same vacuum level as compared to a non-porous application.

SUCTION CUP SELECTION

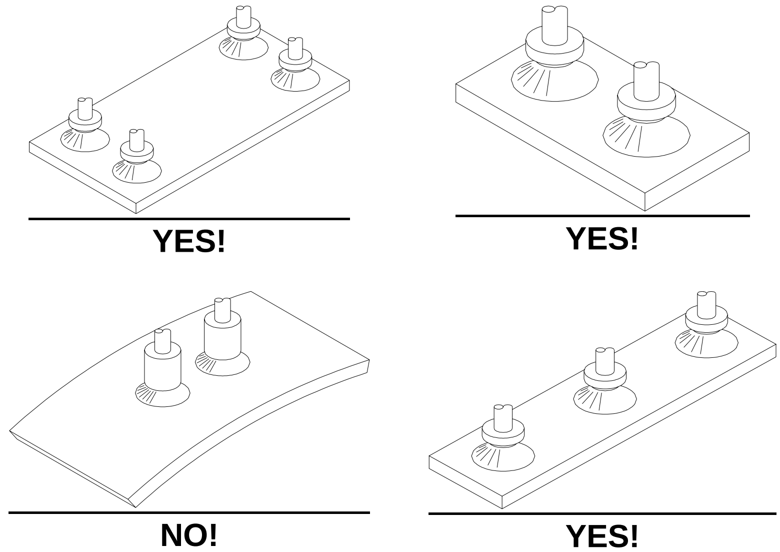
Types of Materials

Suction cups are available in three types of material which would suit different types of applications and environmental conditions:

- Vinyl: Most commonly used, low cost, withstand temperatures up to 150^{o} F, tear resistant.
- Silicone: Used for high temperature applications up to 350^{o} F.
- Rubber: This is also commonly used in most applications.

Suction Cup Positioning

Position the cups in accordance with size, shape, rigidity, etc., of the products being picked up. See the illustrations below.

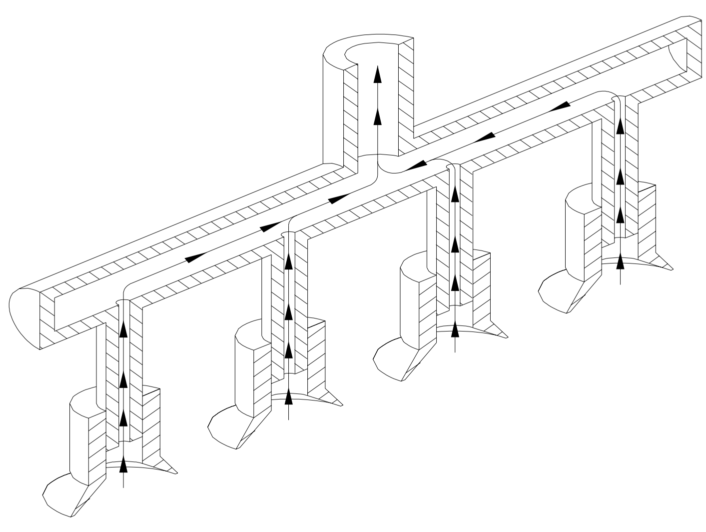


Rigid objects: Place the suction cups in the center or at the corners of the part.

Flexible thin objects: Suction cups should be spread over a wide area of the product as shown above.

Size of Tubing Connecting Cups: For a single suction cup, if the OD of the cup is less than 3/4" use 3/16" or 1/4" ID tubing. If the OD of the cup is greater than 3/4" use 1/4" or 3/8" ID tubing.

For multiple cup connection:



⇒***Rule of Thumb:*** Make sure that the sum of the areas of the individual suction cup line is equal to or less than the area of the main manifold line.

Number of Cups

The porosity of the object or surface being picked up is very important in determining the number of cups to be used. In addition, the load to be lifted/moved and the position in which the load is moved, vertical vs. horizontal, are also determining factors.

Non-Porous Material: Non-porous surfaces are easier to pick up and require fewer cups because they do not allow leakage.

Porous material: To be on the safe side, actual field tests should be performed on porous surfaces or materials. For preliminary designs, derate the holding force by 50% for porous surfaces.

Horizontal Motion:

$$\text{Number of suction cups} = \frac{\text{Load in lbs.}}{\text{Lifting capability of 1cup}}$$

$$\text{Lifting capacity of 1 suction cup} = \frac{0.4912 * \text{cup area} * \text{"Hg vacuum}}{4}$$

This uses a factor of safety of 4 which is sufficient for most applications. You can use a higher factor of safety to be on the conservative side.

Vertical Motion: If the load is moved vertically, and the suction cups are centered, the same procedure may be used but with a multiplier of 0.6 to account for slippage due to jerks and gravity. Notice that at higher altitudes, the vacuum force level will be reduced and actual tests should be performed to determine the safe operating conditions.

Table of Suction Cup Lifting Force
(using the previous formula)

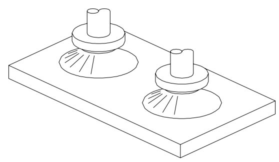
VACUUM								CUP DIAMETER IN INCHES										
IN "HG	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.50	4.00	4.50	5.00	5.50	6.00
5	0.03	0.12	0.27	0.48	0.75	1.09	1.48	1.93	2.44	3.01	3.65	4.34	5.91	7.72	9.77	12.06	14.59	17.36
10	0.06	0.24	0.54	0.96	1.51	2.17	2.95	3.86	4.88	6.03	7.29	8.68	11.81	15.43	19.53	24.11	29.18	34.72
15	0.09	0.36	0.81	1.45	2.26	3.26	4.43	5.79	7.32	9.04	10.94	13.02	17.72	23.15	29.30	36.17	43.76	52.08
20	0.12	0.48	1.09	1.93	3.01	4.34	5.91	7.72	9.77	12.06	14.59	17.36	23.63	30.86	39.06	48.22	58.35	69.44
25	0.15	0.60	1.36	2.41	3.77	5.43	7.38	9.64	12.21	15.07	18.23	21.70	29.54	38.58	48.83	60.28	72.94	86.80

Vacuum Cup Styles

There are three types of suction or vacuum cups – standard, cleated, and bellows styles.

Standard Non-Cleated Cups

This is used for general purpose where uneven surfaces may be encountered and only a small vacuum surface is required to pick up the part. The suction cup surface collapses under vacuum and conforms to the surface.



Cleated Style

These have cleats which act as stand-offs to create a space between the surface and the inside of the suction cup. However, the rim of the suction cup and the bottom surface of the cleats come in contact with the object and reduce the effective vacuum surface area. These cleats act as the threads in an automobile tire to give more friction which helps to hold the part to the cup.

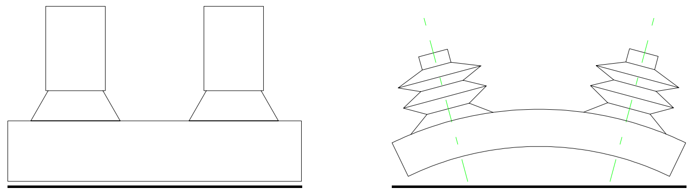
Bellows Style (1, 2, or 3 convolutions)

The unique characteristics of this style cup is its ability to collapse as soon as the cup makes contact with the surface that is being picked up. As the vacuum level increases inside the cup, the object is picked up and can continue in a physical mechanical movement upward without the member to which the cup is mounted making any upward movement. Thus no separate "clearing" upward movement is necessary which may save overall cycle time.

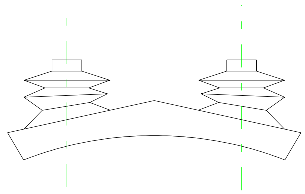
Determining The Number Of Bellows

Selecting the number of bellows mainly depends upon the shape of the surface to be picked up. It also depends upon the approach angle of the suction cup towards the surface.

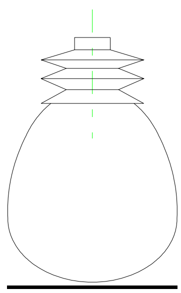
One or Two Bellows: These are used for flat or slightly curved surfaces. When using one or two bellows, the axes of the suction cups need to be perpendicular to the surface.



Three Bellows: Three bellows may be required if the surface is flat yet the axis of the pick-up is not perpendicular to the surface as shown below.



Three bellows is recommended when there is an excessive curvature of surface.



GENERAL GUIDELINES

A combination of a small vacuum generator with a large vacuum cup may theoretically work well under ideal conditions such as when there is a good seal between the suction cup and the surface of the object being picked up. A larger vacuum generator may be needed when:

- a faster response time is needed to reach desired vacuum level and hence faster cycle time.
- it is necessary to overcome a poor seal between the cup and the surface (rough or porous surface, damaged cup edge, etc.)

Should There Be A Dedicated Vacuum Generator For Each Suction Cup?

Using a separate venturi for each cup may be a luxury however in some instances the need for reliability may warrant this. If a single vacuum generator is driving multiple cups, then leakage anywhere in the system or failure of one of the cups to pick up may cause enough vacuum degradation in the other attached cups to hinder or prevent proper pick up. The result of such a failure could be costly.

Multiple vacuum generators may be run in parallel to increase the flow capacity to multiple cups. Remember that the overall air consumption when using multiple generators may be higher than using one larger vacuum generator offering the equivalent vacuum flow and vacuum force level.

Due to flow losses, the vacuum level at the suction cup may be diminished if the vacuum generator is located several feet away.

VACUUM ACCESSORY COMPONENTS

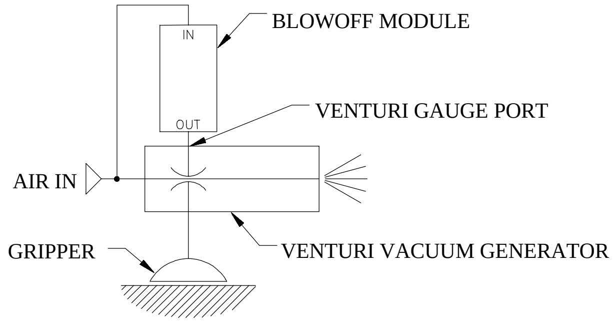
Vacuum Switch

Many systems require some form of feedback for proper machine operation. This is especially helpful in sequencing the pickup arm in a pick-and-place environment. Vacuum switches perform this function and come with either fixed or adjustable set points.

Two types of vacuum switches are available. The electrical vacuum switch is a typical contact switch that can be either a normally open or normally closed contact. Pneumatic vacuum switches are powered from a compressed air source. When the vacuum level reaches the preset level a positive pressure signal appears at the output port of the pneumatic vacuum switch which can be used as a pilot signal for further processing. This device is especially useful in an all-pneumatic control system.

Blow-off Module

This is a useful device when a positive flow of air is required to "quick release" a part from the suction cup at the end of a cycle. The schematic hook-up is shown below.



When the air supply is turned on to establish vacuum, it charges the volume in the blow-off module. The check valve which is built into the module isolates the positive air pressure from the vacuum port. When the air supply to the venturi is turned off, the check valve in the module allows charged air into the vacuum port giving a "puff" of air, thus positively releasing the part from the suction cup. This is useful in labeling applications or wherever the part is light weight and has a tendency to stick to the suction cup even after the vacuum is turned off.

Integrated Vacuum Devices

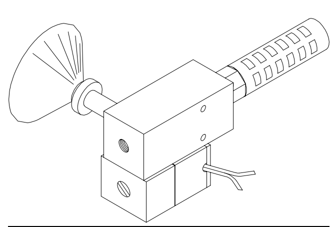
Since venturi vacuum generators and the associated components are small and compact, they can be modularly integrated to offer some unique advantages. This is especially true in factory automation and pick-and-place applications. The advantages of these devices are:

- They offer a vacuum system in component form.
- They are compact.
- Features can be flexibly added or deleted.
- No external plumbing is required, which means less leak, less volume to evacuate and a faster, more responsive system.

Here are a couple of examples of integrated vacuum devices:

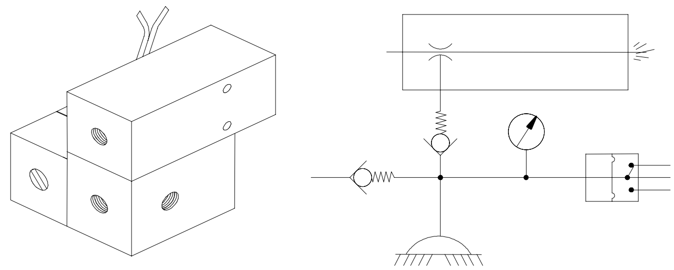
Venturi with Vacuum Switch

This is one of the simplest forms of an integrated device where a vacuum switch is mounted directly on the venturi.



Vac and Hold with Vacuum Switch

This unit provides a critical safety feature in material handling applications, such as transporting windshield glass in automotive plants or in handling large sheet metal parts. This device produces vacuum when the air supply to it is turned on and locks it until a release signal is applied. Thus, even if the air supply is accidentally turned off or if the air line broke off or if there is a need for disconnecting the supply line during transportation, the vacuum is maintained. A vacuum switch can be added in this integrated package to provide additional feedback to the controller.



As the schematic indicates, it utilizes a standard venturi and two other check valves. As the air supply is turned on, the vacuum lines and the suction cup are evacuated through the vacuum lock check valve. The preload on the release check valve is such that the port will stay shut even at the maximum vacuum level. When the air supply to the venturi is turned off, the vacuum check valve has vacuum on one side and atmospheric pressure on the other side. The release check valve is kept shut with the spring force. Thus the vacuum in the gripper area is locked in. When a release signal in the release port is introduced, it overcomes the spring pre-load and not only eliminates the vacuum force but also provides a positive "puff" of air to separate the part from the suction cup.

Other Accessories

Other integrated vacuum devices include a solenoid valve for air supply, a solenoid valve for blow off, flow control valves, parts sensor etc. Even more sophisticated integrated devices can be built by machining the venturi right into the end of arm tooling where work is being performed.