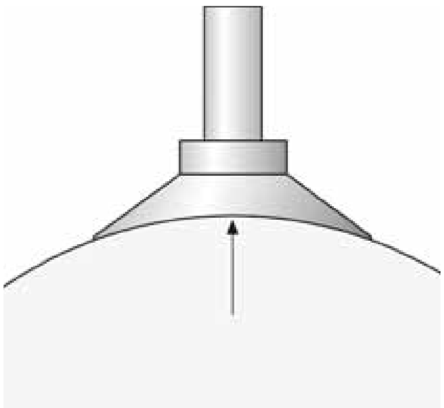
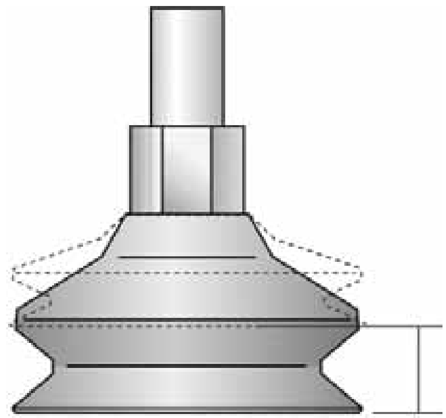
The Vacuum System and its Components

Minimum radius of curvature of the workpiece



Indicates the radius up to which the workpiece can be gripped securely with the respective suction cup.

Suction cup stroke



Refers to the suction cup's stroke (z) that occurs during evacuation of the suction cup.

Design of the Suction Cup

The design of the suction cup always depends on the actual application. For this reason, various physical values must be calculated and determined before the correct suction cup can be selected.

Later in this chapter, the design of a vacuum system is described in more detail based on a calculation example.

Friction coefficient

The friction coefficient "μ" describes the relationship between friction force and normal force. It is not possible to specify generally valid values of the friction coefficient between the suction cup and the workpiece. It has to be determined correctly through trials with the condition of the workpiece surface (rough/dry/moist/oily) or the properties of the suction cup (shape/sealing lip/sealing edge/suction cup material/shore hardness) having a major influence.

Table of typical values Workpiece surface	Friction coefficient approx. μ
Glass, stone, plastic (dry)	approx. 0.5
Sandpaper (dry)	1.1
Moist or oily surface	0.1 – 0.4

Calculation of the holding forces

The calculation of holding forces can only be about theoretical values. In practical applications, many factors, such as the size and shape of the suction cup, the surface finish and the rigidity of the workpiece (deformation) play a decisive role. That is the reason why we recommend a safety factor (S) of at least 2. When swiveling workpieces during the handling task, a safety factor of 2.5 or higher has to be used, in order to cope with the resulting turning forces.

The holding force of a suction cup is the product of:

$$F = \Delta p \times A$$

F = Holding force (without safety factor, purely static)
Δp = Difference between ambient pressure and pressure of the system
A = Effective suction area (the effective area of a suction cup under vacuum)

Suction Cups Continued

Diameter of the suction cup

The holding force of a suction cup depends on its effective diameter. The condition of the workpiece and the number of suction cups are also crucial for the holding force that a vacuum system can generate.

The required diameter can be determined with the aid of the following formula:

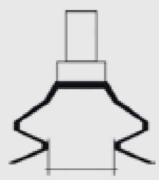
For horizontal pick-up:

$$d = 1.12 \times \sqrt{\frac{m \times S}{P_u \times n}}$$

For vertical pick-up:

$$d = 1.12 \times \sqrt{\frac{m \times S}{P_u \times n \times \mu}}$$

d = Suction cup diameter in cm
(with double lip ~ internal diameter, with bellows suction cup = inner diameter of sealing lip)



m = Weight of the workpiece in kg
P_u = Vacuum in bar
n = Number of suciton cups
μ = Friction coefficient
S = Safety factor

Calculation example for horizontal pick-up:

$$d = 1.12 \times \sqrt{\frac{50\ \text{kg} \times 2}{0.4\ \text{bar} \times 4}}$$

d = 8.85 cm

Plastic sheet: m = 50 kg
Vacuum: P_u = – 0.4 bar
Number of suction cups: n = 4
Measured friction coefficient: μ = 0.5
Safety factor: S = 2

A sensible selection is the suction cup NPFYN 95 with a nominal diameter of 95 mm.

Calculation example for vertical pick-up:

$$d = 1.12 \times \sqrt{\frac{50\ \text{kg} \times 2}{0.4\ \text{bar} \times 4 \times 0.5}}$$

d = 12.5 cm

Plastic sheet: m = 50 kg
Vacuum: P_u = – 0.4 bar
Number of suction cups: n = 4
Measured friction coefficient: μ = 0.5
Safety factor: S = 2

A sensible selection is the suction cup NPFYN 150 with a nominal diameter of 150 mm.

Suction rate or required volume flow [$\dot{V}$]

The volume flow that generates the vacuum is important for the suction force. The workpiece material is the principal factor for the required volume flow.

The table shows typical values for the volume flow or suction rate depending on the diameter of the suction cup with smooth and air-tight surface.

Important:
Conduct suction trials for porous parts.

Typical value (with smooth, air-tight surfaces)			
Suction cup Ø	Suction area A	Volume flow	
	(cm²)	(m³/h)	(l/min)
up to 60 mm	28	0.5	8.3
up to 120 mm	113	1.0	16.6
up to 215 mm	363	2.0	33.3
up to 450 mm	1,540	4.0	66.6

Specialty Grippers

Special grippers are used in applications in which regular suction cups cannot be used. Special grippers are used to handle wafers, films, paper, fragile workpieces or textile fiber composites. They serve as a connection element between the workpiece and the handling system just like the suction cup.

- Numatics separates special grippers into the following series:
- Floating suction grippers
- Magnetic grippers

Large Area Grippers

The NFX Series large area gripper is designed to handle work-pieces with a wide range of dimensions and/or undefined positions. It provides customers with a reliable means of handling work-pieces that have several gaps.
Applications include palletizing/depalletizing, in addition to order picking and sorting of a wide range of work-pieces with a single gripper. Typical work-piece materials include cardboard, wood, metal or plastic.

Floating Suction Gripper

Floating suction grippers are pneumatically operated special grippers with integrated vacuum generation. They operate on the Bernoulli principle and work as a low-contact system. The workpiece "floats" on an air cushion at the gripper surface. This makes the floating suction gripper ideally suited for the handling of very sensitive products. The high volume flow can compensate for leakage, when handling porous workpieces.

Advantages of floating suction grippers:
- Low-contact handling
- High volume flow
- Safe separation of thin, porous workpieces
- Integrated vacuum generation

Typical areas of application:
- Handling of fiber composites, paper, film, wood veneer, printed circuit boards, wafers and solar cells
- Separation of thin, porous workpieces

Magnetic Gripper

Magnetic grippers provide safe gripping of ferromagnetic workpieces by using the magnetic field of an integrated permanent magnet. The magnet is moved with compressed air to activate and deactivate gripping. Magnetic grippers are operated with pneumatic valves. The gripper does not require a voltage source for this purpose.

Advantages of magnetic grippers:

- Safe gripping with a permanent magnet is possible without voltage source
- Control of permanent magnet with compressed air or vacuum

Typical areas of application:

- Handling of ferromagnetic workpieces
- Handling of blanks and perforated plates as well as sheet metal parts with drilled holes/breakouts or complex shapes
- Support of vacuum gripping system in highly dynamic handling of sheet metal parts

Mounting Elements

Numatics offers a broad product range of mounting elements to integrate grippers (suction cups or special grippers) into gripping systems.

The following mounting elements can basically be distinguished:

- Holders and adapters
- Spring plunger
- Jointed mountings

For additional information and ordering details, refer to the chapter "Mounting Elements."

Mounting Elements Continued

Holders and adapters

The suction cups are attached to the basic structure or the traverse with holders and adapters. Different types of aluminum sections or square and round tubes are available.

Spring plungers

Spring plungers are used to compensate height differences of workpieces. They also cushion the impact of the suction cup and allow handling of fragile workpieces.

Jointed mountings

Jointed mountings provide a better adaption of the suction cup to the workpiece due to the design of Flexolink NFLK and ball joint NKGL that can be swiveled in all directions.

Suction cups

(chapter “Vacuum Suction Cups” or “Special Grippers”)

Vacuum Generators

Vacuum generators provide the vacuum level that is required for the handling task. The vacuum is created either pneumatically or electrically.

Pneumatic vacuum generators implement short cycle times and can be integrated directly into the system due to their compact and lightweight design.

Electrical vacuum generators are used in applications when compressed air is not available or when very high suction capacities are required.

Pneumatic vacuum generators

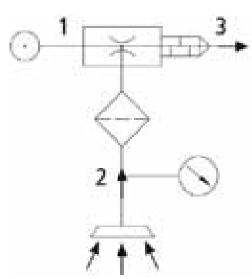
- Ejectors

Electrical vacuum generators

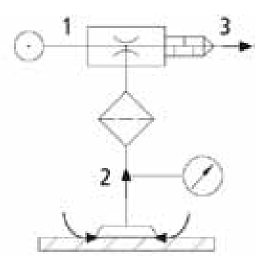
- Pumps

Important

The nominal suction rate of all vacuum generators is given in l/min or m3/h. The values are based on an ambient pressure of 1,013 mbar (sea level) and an ambient temperature of 20 °C. The maximum suction rate therefore indicates the volume flow that the vacuum generator evacuates from the environment (free flow).



Free pick flow



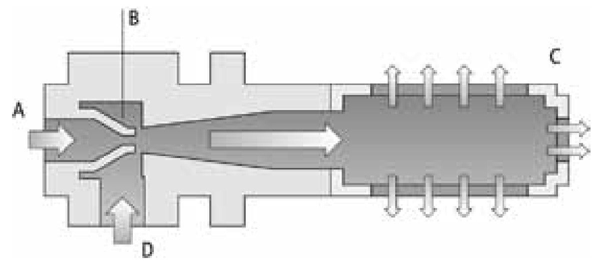
Additional suction while workpiece is picked up

Vacuum Generators Continued

Ejectors work on the Venturi principle. They are divided into single-stage and multi-stage ejectors depending on the number of nozzle pairs.

The compressed air is supplied through the connection (A) to the single-stage ejectors. It flows through the Venturi nozzle (B). The air is accelerated and compressed during this process.

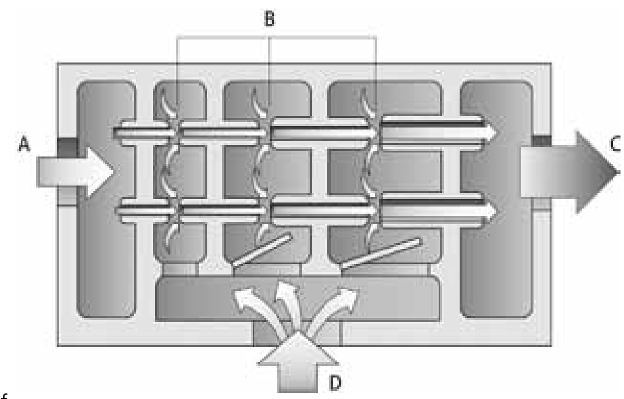
After passing through the nozzle, the accelerated air expands once again and a vacuum is created. Air is drawn in this way through the vacuum connection (D). The air that was drawn in and the compressed air escape through the silencer (C).



Principle of operation of a single-stage ejector

The Numatics basic ejectors, inline ejectors and compact ejectors are based on the single-stage Venturi principle.

In addition to the single-stage Venturi principle, there are ejectors in which the vacuum is created by several Venturi nozzles arranged in a row. Compressed air is supplied to the ejector through con- nection (A). It passes through several Venturi nozzles (B) arranged in a row. A vacuum is created and the air is drawn in through the vacuum connection (D). The suction volumes of the individual nozzles add up to form a total suction rate D. The air that was drawn in and the compressed air escape through the silencer (C).



Principle of operation of a multi-stage ejector

Compared to single-stage ejectors, multi-stage ejectors create a much higher suction rate in the lower vacuum range using the same amount of compressed air.

The Numatics multi-stage ejectors are based on the multi-stage Venturi principle.

Advantages of ejectors:

- Compact
- Low weight
- Fast vacuum generation
- No flexible parts, resulting in low maintenance and low wear
- Choose an installation position
- No heat generation

Typical areas of application:

- Industrial robot applications in all industries, such as feeder applications in the automotive industry

Vacuum Generators Continued

We distinguish between three basic types of ejectors:

Basic and inline ejectors

- Vacuum generators without valve control and system monitoring with high maximum vacuum level (85% vacuum)
- Used mainly to handle air-tight workpieces

Multi-stage ejectors

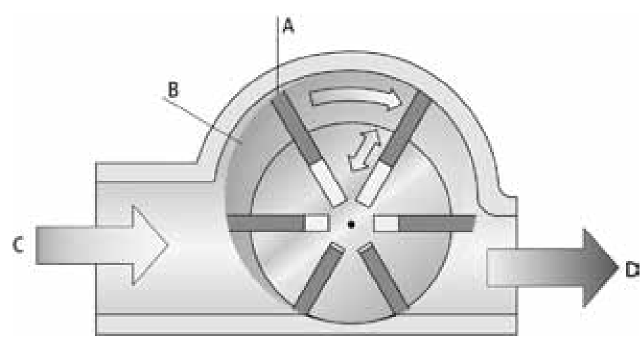
- Vacuum generators with several nozzle chambers arranged in a row with a very high suction rate.
- Used mainly for handling porous workpieces, such as cardboard, chipboards, OSB or MDF sheets

Compact ejectors

- Vacuum generators with integrated valve technology and system monitoring, NSCP*I* series are equipped with IO-Link technology
- Control of pick-up and blow-off feasible without external valves
- Optional with integrated air-saving regulation
- Used in fully automatic handling systems (e.g. sheet metal processing, automotive industry, robot applications)

Vacuum Pumps

Vacuum pumps include an eccentrically mounted impeller with carbon vanes (A) which are pressed against the walls of the housing by centrifugal force and thus provide a seal. As the impeller rotates, the size of each chamber (B) varies. As the chamber becomes larger, the air in it expands and the pressure drops, resulting in a partial vacuum. The air is drawn in through the inlet (C), compressed, and ejected through the outlet (D).
Due to their high compression factor, pumps generate a very high vacuum and, according to the type, have a very high suction capacity.



Advantages of vacuum pumps

- High vacuum with high evacuation volume
- Central vacuum generation

Typical areas of application

- As central vacuum generation in gantry handling systems
- In manual vacuum handling systems
- In packaging machines

- Universal vacuum pumps requiring little maintenance
- Used mainly as central vacuum generator in large gripping systems for handling air-tight workpieces

Switches and System Monitoring

Devices for system monitoring are important for the safe operation of a vacuum system. Numatics offers measuring as well as control components for this purpose.

We distinguish between the following components for system monitoring and control:

- Vacuum switches
- Pressure switches
- Combined vacuum/pressure switches
- Connection cable and adapter for vacuum switches
- Measuring and control components

Components for system monitoring are used in all areas of automated handling applications, for example, in feeder systems in the automotive industry, in the plastics industry, as well as in other applications in order to increase process safety.

Vacuum Switches

Vacuum switches are available in mechanical and electronic types. In the mechanical versions, the existing vacuum is measured by using a membrane, or a valve (pneumatic design) is activated. In the electronic version, the vacuum is measured by a piezoresistive sensor and a switching signal (analog or digital) is output.

Vacuum Switches Continued

Vacuum switches are used in the measuring range from -1 to 0 bar. There are the following types of vacuum switches:

Mechanical vacuum switches

Mechanical vacuum switches are characterized by their sturdy design and their universal operating principle. The pneumatic design (PM), does not require electrical connections. It works purely with pneumatics. You can set the switching points (with fixed hysteresis) to adapt these switches individually to the process parameters.

Electronic vacuum switches

Electronic vacuum switches have a high switching accuracy and repeatability with a very compact design. Vacuum switches with digital display offer a high level of convenience, because the switching points and hysteresis are fully programmable using a foil keypad. To program the switching point in a process rather quickly and simply, use vacuum switches with teach button. You can program the switching points with this version using a key in a matter of seconds. Vacuum switches with analog and digital output and vacuum switches in miniature form round off the program.

Pressure Switches

Electronic pressure switches are used in the measuring range from 0 to 10 bar. Pressure switches with digital display are easy to operate. The switching points and hysteresis are fully programmable using a foil keypad. They are used when there are high requirements for switching accuracy and repeatability as well as implementation of short switching times. Pressure switches with teach button are particularly suited to program switching points quickly and easily. Pressure switches with analog and digital output can also be used as pressure sensors due to their two outputs.

Combined Vacuum/Pressure Switches

Combined vacuum/pressure switches are used in the measuring range from -1 to 10 bar. The switching accuracy is reduced by the large measuring range. They are available with two switching outputs (digital and analog) and can also be used as a vacuum sensor or a pressure sensor for this reason.

Connections and Adapters for Vacuum Switches

Matching connection cables and adapters are available for the different types of switches. The cables and connectors are adapted to meet the customer-specific requirements and local standards.

Measuring and Control Components

Vacuum regulators can be adjusted mechanically. They provide a precise setting with high repeatability. Vacuum regulators compensate for pressure differences of vacuum generators caused by their design.

Filters and Connectors

Vacuum systems are protected by the use of filters. The filters protect the vacuum generator from contamination. Suction cups and vacuum generator are connected with each other by hoses and connectors.

Vacuum Filters

Filters are used to protect the vacuum generator or the valve in dusty environments. The filters are installed in the system between the suction cup and the vacuum generator or the valve.

Vacuum filters are often installed as central filter in the system. The vacuum filters have a degree of separation of almost 100%.

Vacuum cup filters are installed as decentralized filters directly in the vacuum line at the suction cup. Vacuum cup filters are used with light to medium contamination.

Inline filters are installed as decentralized filters directly in the vacuum line at the suction cup. Inline filters are used with small flows and light contamination.

Check valves interrupt the flow as soon as a certain volume flow has been reached. This will turn off any suction cups in the gripper system that may not be covered completely. The system vacuum will remain intact.

Definition of Vacuum

Vacuum is the term for air pressures which lie below normal atmospheric pressure. The ambient pressure is 1,013 mbar (14.7 PSI) at sea level and decreases with elevation.

The form of the vacuum depends on the application in vacuum technology. A relatively small vacuum, the low vacuum, is sufficient for vacuum handling.

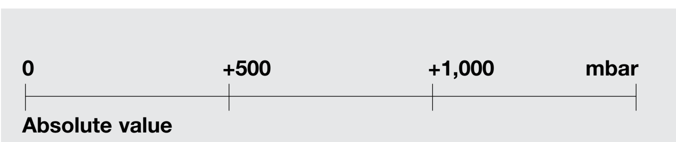
The pressure of the low vacuum ranges from 1 mbar (0.015 PSI) to 1,013 mbar (14.7 PSI); at sea level (ambient pressure)

Specification as relative value

In vacuum technology, the vacuum is specified as a relative value which means the vacuum is specified in relation to the ambient pressure. Such vacuum values always have a negative sign, because the ambient pressure is used as the reference point, which is defined as 0 mbar.

Specification as absolute value

In science, a vacuum is specified as an absolute value. The reference point is absolute zero, which means space void of air (e.g. outer space). This means the vacuum value is always positive.



The following table shows the comparison values between absolute and relative pressure.

Vacuum/pressure conversion table								
Absolute pressure (mbar)	Relative Vacuum	Bar	N/cm^2	kPa	atm, kp/cm^2	mm H_2O	Torr; mm Hg	in Hg
8.00	6.62	5.64	4.74	3.81	3.01	2.28	1.42	0.40
16.10	13.60	11.37	9.03	7.25	5.63	3.97	2.65	1.10
37.70	33.20	30.10	26.70	23.00	18.60	14.90	9.80	5.20
71.00	65.00	60.10	52.00	44.00	36.50	29.00	20.50	11.40
127.00	117.80	106.00	94.20	79.10	65.30	49.87	35.99	23.00
215.00	172.00	156.10	138.70	118.50	99.10	79.36	58.90	37.24

At the end of this chapter you will find additional conversion and unit tables.

Measurement Units for Vacuum Data

The units pascal [Pa], kilopascal [kPa], bar [bar] and millibar [mbar] are most widely used in vacuum technology as units for pressure. The units are converted as follows:

0.001 bar = 0.1 kPa = 1 mbar = 100 Pa

In this catalog, all absolute pressure values are given in bar or mbar, all relative values in %. The % value is typical for a relative indication of the efficiency of a vacuum generator. Other units are used internationally. Some of them are included in the following table.

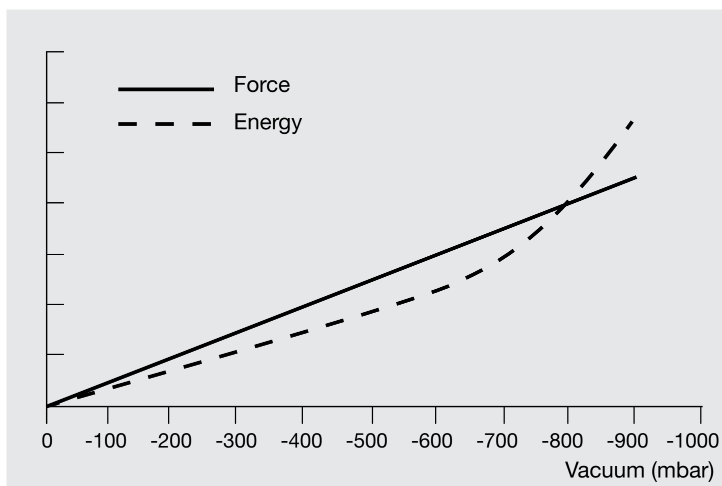
Vacuum/pressure conversion table							
	Bar	**N/cm²**	**kPa**	**atm, kp/cm²**	**mm H_2O**	**Torr; mm Hg**	**in Hg**
Bar	1.00000	10.00000	100.0000	1.01970	10,197.00	750.0600	29.5400
N/cm²	0.10000	1.00000	10.0000	0.10190	1,019.70	75.0060	2.9540
kPa	0.01000	0.10000	1.0000	0.01020	101.97	7.5006	0.2954
atm, kp/cm²	0.98070	9.80700	98.0700	1.00000	10,332.00	735.5600	28.9700
mm H_2O	0.00010	0.00100	0.0100	0.00000	1.00	0.0740	0.0030
Torr; mm Hg	0.00133	0.01333	0.1333	0.00136	13.60	1.0000	0.0394
in Hg	0.03380	0.33850	3.8850	0.03446	345.40	25.2500	1.0000

At the end of this chapter you will find additional conversion and unit tables.

Energy Required for Vacuum Generation

The energy required for vacuum generation increases dispropor- tionately to the attained vacuum. Increasing the vacuum from -600 mbar to -900 mbar, for example, increases the holding force by a factor of 1.5, but the evacuation time and the energy needed to achieve this vacuum value increases by a factor of 3.

This means that only the vacuum required should be generated in the working area to keep the energy expenditure and the operating costs at a minimum.



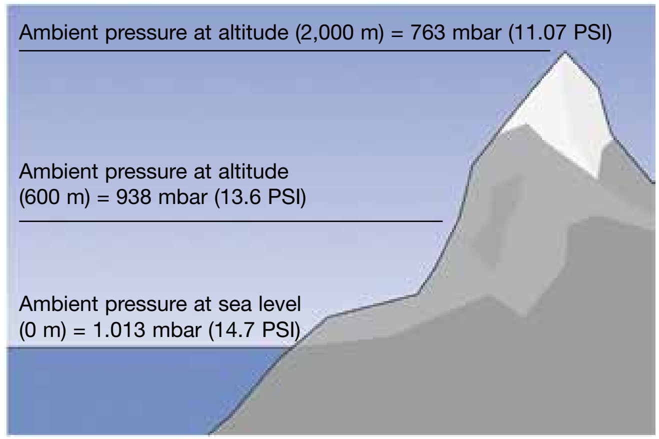
Common working areas

- for air-tight surface (e.g. metal, plastics, etc.): -600 to -800 mbar vacuum
- for porous materials (e.g. cardboard boxes, particle boards, MDF sheets, etc.): -200 to -400 mbar vacuum; in this range the necessary holding force is generated by increasing the suction rate and the suction area.

Important:

In this catalog, the holding forces of the suction cups are always specified at an efficient vacuum level of -600 mbar.

The Atmosphere and its Effects on Vacuum Technology



The air pressure (ambient pressure) depends on the elevation of the location as well as the temperature at that site. As shown in the diagram, the air pressure at sea level is 1,013 mbar (14.7 PSI). Elevation of 600 m air pressure is reduced to 938 mbar (13.6 PSI). At a height of 2,000 m, the air pressure is only 763 mbar (11.07 PSI).

This pressure loss also has an effect on working with a vacuum. The pressure drop with increasing height also reduces the maximum pressure difference that can be attained and therefore the maximum holding force. Per 100 m increase in elevation, the air pressure drops by about 12.5 mbar (0.18 PSI).

A vacuum generator that generates an 80% vacuum, achieves a vacuum value of -810 mbar at sea level (ambient pressure = 1,013 mbar); at 2,000 m (ambient pressure = 763 mbar) a vacuum generator only achieves -610 mbar. The possible holding force of a vacuum suction cup drops proportionally to the vacuum value that can be attained. This means the application at sea level presents the best case scenario.

Important:

All data in this catalog refer to an ambient pressure of 1,013 mbar (14.7 PSI) and an ambient temperature of 20 °C.

Approach to System Design

The implementation from theory to practice is shown with a system design based on an example.

1	2	3	4	5	6	7	8
Calculation of forces	Suction cups	Mounting elements	Vacuum hoses	Distributors	Vacuum generators	Numatics Valves	Vacuum switches

Flowchart for system design

The following calculations are based on this application:

Workpiece

Material:	Steel sheets, stacked on a pallet	
Surface:	Smooth, level, dry	
Dimensions:	Length: max. 2,500 mm	
	Width: max. 1,250 mm	
	Thickness: max. 2.5 mm	
	Weight: approx. 60 kg	

Handling system

Used system:	Gantry handling system	
Existing compressed air:	8 bar	
Control voltage:	DC 24 V	
Working sequence:	Horizontal Pick & Place A steel sheet is picked up from a pallet, lifted, transported horizontally and deposited in a machining center.	
Max. acceleration:	X, Y axis:	5 m/s^2
	Z axis:	5 m/s^2
Cycle time:	30 s	
Scheduled time:	for pick-up:	< 1s
	for releasing:	< 1s

Weight Calculation of a Workpiece

It is important to determine the weight (m) of the workpiece to continue with additional calculations. It is calculated based on the following formula:

$m = L \times B \times H \times \rho$

m = Weight (kg)

L = Length (m)

B =Width (m)

H = Height (m)

ρ = Density (kg/m3)

Our example:

$m = 2.5m \times 1.25m \times 0.0025m \times 7{,}850 kg/m^3$

m = 61.33kg

Theoretical Holding Force of a Suction Cup

The suction cups not only have to be able to carry the weight of the workpiece but must also be capable of handling the acceleration forces. These may never be neglected in a fully automated process.

To calculate the theoretical holding force, we show and describe the three most important and most frequently occurring load cases (handling sequences).

Important:

For the following, simplified representations of the load cases the calculation must be based on the worst load case with the highest, theoretical holding force. This is the only way to ensure that the suction cup grips the workpiece safely during the entire handling process.

The safety factor is a minimum value of 1.5 for smooth and dense workpieces. A safety factor of 2.0 or greater must be used for cri tical, diverse or varied, porous or rough workpieces. If factors such as acceleration or friction coefficient are not known or cannot be deter- mined precisely, a value of 2.0 or higher should also be used.

Load case I – Suction cup horizontal, direction of force vertical

The workpiece (in this case the steel sheet with the dimensions 2.5 x 1.25 m) is lifted from a pallet. The workpiece is lifted with an acceleration of 5 m/s2 (no transverse movement).

$F_{TH} = m \times (g + a) \times S$

F_{TH} = theoretical holding force (N)

m = Weight (kg)

g = Gravity (9.81 m/s^2)

a = Acceleration (m/s^2) of the system

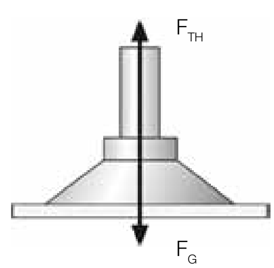
S = Safety factor (minimum value 1.5 times safety;

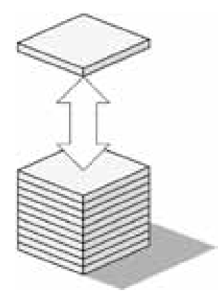
for critical, diverse or varied or porous materials or rough surfaces 2.0 or even higher)

Our example:

$F_{TH} = 61.33 kg \times (9.81 m/s^2 + 5 m/s^2) \times 1.5$

F_{TH} = 1,363 N





The suction cups land on a workpiece vertically that is to be lifted up.

Theoretical Holding Force of a Suction Cup Continued

Load case II – Suction cup horizontal, direction of force horizontal

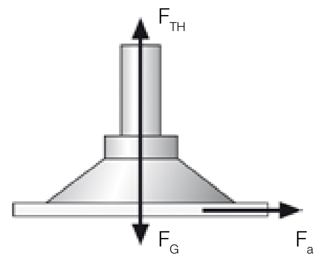
The workpiece (in this case the steel sheet with the dimensions 2.5 x 1.25 m) is lifted up vertically and transported horizontally. The acceleration is 5 m/s^2.

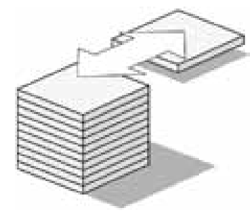
F_{TH} = m x (g + a/μ) x S

F_{TH} = theoretical holding force (N)
F_a = Acceleration force = m · a
m = Weight (kg)
g = Gravity (9.81 m/s^2)
a = Acceleration (m/s^2) of the system (keep in mind Emergency Stop situations!)
μ = Friction coefficient = 0.1 for oily surfaces
= 0.2 to 0.3 for wet surfaces
= 0.5 for wood, metal, glass, stone etc.
= 0.6 for rough surfaces

Caution! The specified values for friction coefficient are averaged and must be checked for the individual workpiece!

S = Safety (minimum value 1.5 times safety, for critical, diverse or varied or porous materials or rough surfaces 2.0 or even higher)





The suction cups land on a workpiece horizontally that is to be moved to the side.

Our example:

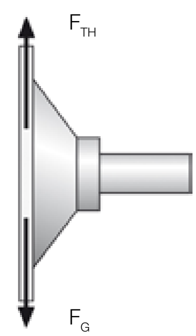
F_{TH} = 61.33 kg x (9.81 m/s^2+ 5 m/s^2) x 1.5
F_{TH} = 1,822 N

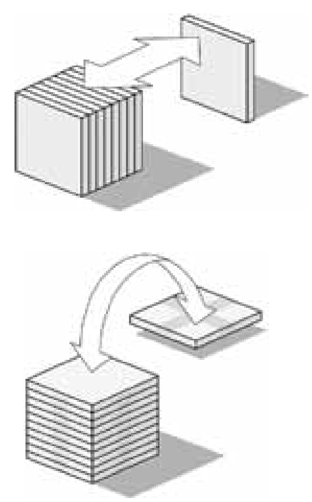
Load case III – Suction cup vertical, direction of force vertical

Description of load case: The workpiece (in this case the steel sheet with the dimensions 2.5 x 1.25 m) is picked up from a pallet and moved with a rotary motion at an acceleration of 5 m/s^2.

F_{TH} = (m/μ) x (g + a) x S

F_{TH} = theoretical holding force (N)
m = Weight (kg)
g = Gravity (9.81 m/s^2)
a = Acceleration (m/s^2) of the plant (keep in mind Emergency Stop situations!)
μ = Friction coefficient = 0.1 for oily surfaces
= 0.2 to 0.3 for wet surfaces
= 0.5 for wood, metal, glass, stone etc.
= 0.6 for rough surfaces
S = Safety (minimum value 2.0 times safety, forcritical, diverse or varied or porous materials or rough surfaces even higher)





Our example:

F_{TH} = 61.33 kg x (9.81 m/s^2+ 5 m/s^2) x 1.5
F_{TH} = 1,822 N

Comparison:

For our scenario, the workpiece is lifted off a pallet, moved to the side and placed on a machining center. The rotary motion from load case III is not needed in this application, therefore one only needs to consider the result from load case II.

The result in this case is a maximum theoretical holding force (F_{TH}) of 1,822 N. This theoretical holding force acts on the suction cup during horizontal transport of the workpiece. The following calculations are based on this value to safely solve the task.

Suction Cup Selection

The calculated theoretical holding force corresponds to the force that the suction cups must create to safely handle the workpiece. To select the suction cups, one must also take the ambient conditions and the application into consideration.

The selection of the suction cups usually takes place based on the following criteria:

Application: The operating conditions on site are crucial for the selection of the suction cup, such as multi-shift operation, service life, chemically aggressive environment, temperature.

Material: Suction cups made of different materials are available to meet the requirements, such as those particularly suited for smooth or rough surfaces, oily or very fragile workpieces, anti- static suction cups for electronic components, suction cups leaving few marks for fragile plastic parts, etc. The selection of the suitable suction cup material for handling of workpieces is described in a comprehensive table in the chapter “Vacuum Suction Cups”.

Surface: Depending on the condition of the surface, we recom- mend suction cups in specific shapes. You can select from flat or bellows suction cups with different sealing lips and sealing edges in different shapes and geometries. An overview of the different suction cups and the specific advantages of the individual suction cup types is included in the chapter “Vacuum Suction Cups”.

For this example we choose:
Flat suction cup of the type NPFYN made of Nitrile (NBR)

This suction cup is a cost-efficient solution for handling smooth, level workpieces. Data for this type is available on the respective pages in the chapter “Vacuum Suction Cups”.

To solve the example, the calculated theoretical holding force can be applied by one suction cup or distributed among several suction cups. The number of suctions cups used depends on the respective application.

For the steel sheet (2,500 x 1,250 mm) from the present case, one would usually use six or eight suction cups. The most important criterion for the number of suction cups in this example, is the flexing of the steel sheet during transport. Depending on the number of used suction cups, the required diameter of these suction cups changes.

Calculation of suction force FS [N] for individual suction cup

$$F_S = F_{TH}/n$$

F_S = Suction force
F_{TH} = Theoretical holding force
n = Number of suction cups

Our example: $F_S = 1{,}822\ N/6$

$F_S = 304\ N$

According to the technical data for the suction cup NPFYN, one needs 6 x NPFYN 95 NBR with a diameter of 95 mm and a suction force of 350 N each.

$F_S = 1{,}822\ N/8$

$F_S = 228\ N$

According to the technical data for the suction cup NPFYN, one needs 8 x NPFYN 80 NBR with a diameter of 80 mm and a suction force of 260 N each.

For this example we choose:
Six suction cups of type PFYN 95 NBR

With a sheet thickness of 2.5 mm, six suction cups ensure a secure sheet pick.

Important:

- The suction force of the individual suction cups is listed in the table “Technical data” for the respective suction cup in the chapter “Vacuum Suction Cups”.
- The suction force of the suction cup must exceed the calculated theoretical holding force.

Mounting Element Selection

The mounting of the suction cups is usually selected according to customer requirements. But there may be compelling reasons for a particular type of mounting:

Uneven or inclined surfaces

The suction cup must be able to adapt to the incline:
> Joint mounting

Different heights/thicknesses

To compensate for height difference, one needs a spring-supported mounting:
> Spring plunger

In this case, the steel sheets are stacked on a pallet. If the sheets are larger than the pallet, one must assume that the ends of the sheets are hanging down. This means the suction cups must be able to compensate for height differences and inclines.

For this example we choose:
Joint Flexolink NFLK 1/4" – 1/4" female thread

Optimum flexibility of suction cups for inclined workpiece surfaces.

Spring plunger NFSTE 1/4" – 75 stroke

Greatest stroke because of sheets hanging down from pallet, 1/4" thread for connection to selected joint mounting Flexolink NFLK.

Note:

Make sure when you select the mounting elements that these can be screwed onto the suction cups, which means the threads have to match. This also ensures maintaining the carrying capacities. The different mounting options and technical data are listed in the chapter “Mounting Elements”.

Vacuum Generator Selection

The selection of the matching vacuum generator (ejector or pump) is determined by several factors:

- Type of workpieces: Porous, air-tight
- Energy supply options: a lower case electricity, compressed air
- Restrictions for size and weight
- Maintaining cycle times
  Short cycle times: Ejector
  Long transport distances: Pump

For this example we choose:

Ejector Because the workpiece in this case is air-tight, you can create a simple and lightweight structure while implementing short pick-up and release times.

Selection table for generator type by application								
	Materials		Cycle times		Power Supply		Transport Path	
	Air-tight	Porous	Very Short <0.5 sec	Short >0.5 sec	Compr. air	Electricity	Short	Long
Ejector	X		X		X		X	(X)*
Pump	X			X		X		X
Blower		X		X		X		X

* Only with automatic air-saver (LSP) and air-tight materials

Vacuum Generator Selection Continued

Suction rate of vacuum generator

The diameter of the suction cup determines the suction rate that a vacuum generator has to apply to evacuate the suction cup. The suitable suction rate is described in the table "Technical data" of the respective vacuum generator.

Based on experience and measurements with system designs, we recommend a selection based on the following table:

Suction capacity as a function of suction-cup diameter			
Suction cup Ø	Suction capacity V_s		
Up to 60 mm	0.5 m^3/h	8.3 l/min	.29 SCFM
Up to 120 mm	1.0 m^3/h	16.6 l/min	.58 SCFM
Up to 215 mm	2.0 m^3/h	33.3 l/min	1.16 SCFM
Up to 450 mm	4.0 m^3/h	66.6 l/min	2.33 SCFM

Note:

The specified values apply regardless of the type of vacuum generation. The recommended suction ratio applies per suction cup and only for smooth, air-tight surfaces. For porous, permeable workpieces we recommend conducting a corresponding suction trial with the original workpiece.

Calculation of the suction rate V [m3/h, l/min], that the vacuum generator has to apply

$$V = n \times V_s$$

n = Number of suction cups

V_s = Required suction rate for an individual suction cup (m3/h, l/min)

Example: **V = 6 x 16.6 l/min**
V = 99.6 l/min

For this example we choose:
Compact ejector NSCPI 20 with a suction rate of 140 l/min.

The compact ejector offers valves for control of the "suction" and "blow off" functions as well as system monitoring for ensuring process safety during handling. The compact ejector NSCPI is also equipped with IO-Link Technology. It makes the various diagnostic functions visible and usable on the control level. This increases system availability and makes automation processes even more efficient.

Valve Technology Selection

In this case we are using a compact ejector with integrated valve technology. In other cases we need solenoid valves to switch the function "Vacuum on/off". They are usually used when pumps are used as vacuum generators. The selection of the valves is based on the following criteria:

- Suction rate of vacuum generator
- Control voltage
- Operating principle of the valve (NO/NC)

The nominal flow of the solenoid valve may not be less than the suction ratio of the vacuum generator. Refer to the valves section of the Numatics catalog if external valves are required.

Calculation of the suction rate V [m3/h, l/min], that the vacuum generator has to apply

$$V = n \times V_s$$

n = Number of suction cups

V_S = Required suction rate for an individual suction cup (m3/h, l/min)

The nominal flow is listed in the "Technical data" of the respective valve and the suction rate is listed in the "Technical data" of the respective vacuum generator.

Example: $V_v = 116$ l/min $= 7$ m³/h

For this example we choose:

The used compact ejector of type SCPI 20 is equipped with solenoid valves which eliminates the need for separate valves.

Switches/Sensors Selection

Vacuum switches and manometers are usually selected based on the existing requirements regarding functionality and switching frequency.

The following functions are available:

- Adjustable switching point
- Hysteresis fixed or adjustable
- Signal output digital and/or analog
- Function LED
- Display with input keyboard
- Vacuum connection M5-F, M8-F, flange or tube insert
- Supply and signal connection with cable or M8 plug

The available versions with their respective technical data are explained in the chapter "Sensors, Switches and Regulators".

For this example we choose:

The used compact ejector of the type NSCP*I* 20 is equipped with an integrated system monitoring (digital output signals). There is no need for an additional vacuum switch.

You can use vacuum switches or manometers for vacuum generators without system monitoring.

Calculation of Evacuation Times

The entire volume that has to be evacuated is required to calculate the efficiency of the vacuum system.

$$V_G = V_1 + V_2 + V_3 + V_4 + V_5 + ...$$

V_G = Volume to be evacuated (m^3)
V_1 = Volume of suction cups (m^3)
V_2 = Volume of mounting elements (m^3)
V_3 = Volume of vacuum hoses (m^3)
V_4 = Volume of distributor (m^3)
V_5 = Volume of prefilter (if necessary) (m^3)
V_6 = Volume of solenoid valve (if necessary) (m^3)
...

Example:

$$V_G = 6 \times 32\ cm^3 + 6 \times 9.5\ cm^3 + 6 \times 43\ cm^3 +1 \times 38.5\ cm^3$$

$$V_G = 546\ cm^3 = 0.000546\ m^3$$

Calculation of evacuation time t (h)

$$t = (V_G \times \ln (P_a/P_e) \times 1.3)/V$$

V_G = Volume to be evacuated (m^3)
ln = Natural logarithm
P_a = Absolute start pressure (1,013 mbar)
P_e = Absolute final pressure (mbar)
V = Suction rate of vacuum generator (m3/h)

Example:

$$t = (0.000546\ m^3 \times \ln (1{,}013\ mbar / \underbrace{400\ mbar}_{60\% = 400\ mbar\ absolute}) \times 1.3) / 6.95\ m^3$$

$$t = 0.0000949\ h = 0.34\ sec$$

The evacuation time of the entire system is 0.34 seconds. The system is cost-optimized and efficient, shorter cycle times are possible.

Test with Original Parts

The example listed above provides a recommendation ratio on a theoretical system design. It is recommended to perform testing using actual work pieces. If required, we will assist and and provicde test analysis

Symbols in Vacuum Technology

Circuit diagrams and function charts are used in vacuum technology to visualize vacuum systems. These diagrams/charts include symbols for certain components or modules. The following overview represents the most important and common symbols of vacuum components from Numatics.

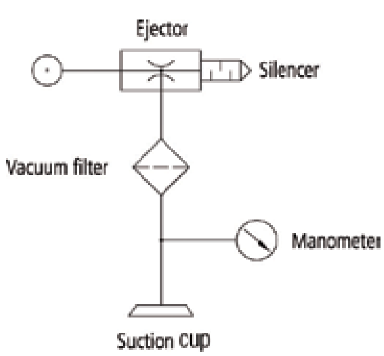
	Valve (general)
	Ball cock, two-way
	Ball cock, three-way
	Manual slide valve, three-way
	Solenoid valve, 3/2-way
	Solenoid valve, 3/2-way, pneumatic pilot operation
	Filter
	Manometer

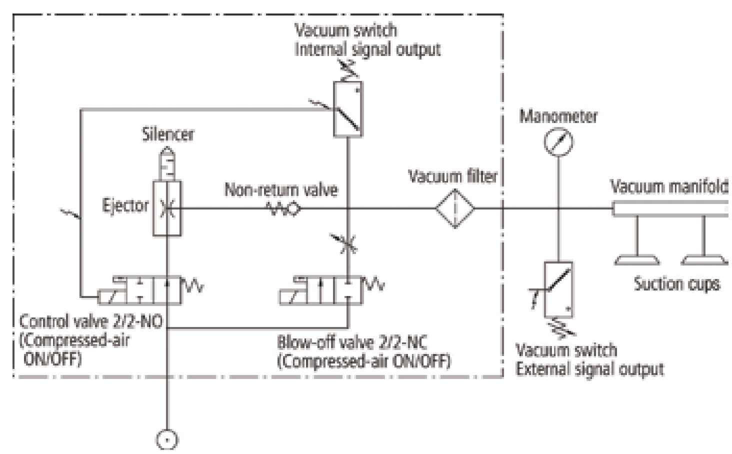
	Vacuum/pressure switch
	Check valve
	Pressure-limiter valve
	Non-return valve
	Sensing valve
	Flow resistor

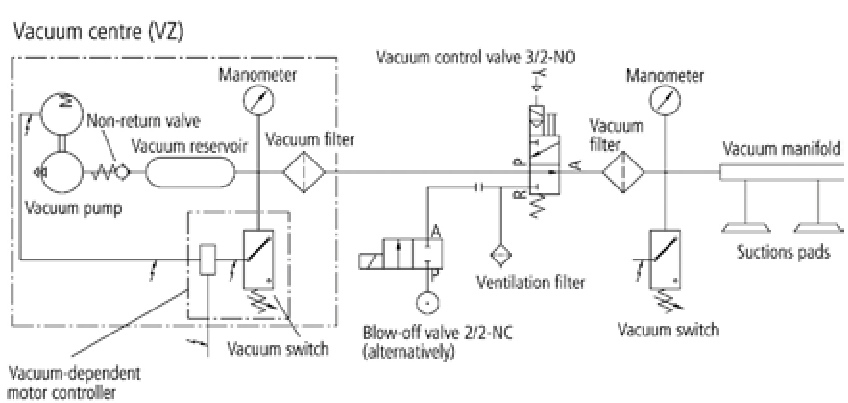
	Special suction cup
	Flat suction cup with single lip
	Flat suction cup with double lip
	Flat suction cup with sealing profile
	Bellows suction cup
	Spring plunger
	Flexolink, ball joint
	Sealing cord
	Adapter nipple

	Ejector, single-stage
	Ejector, multi-stage
	Silencer
	Vacuum blower
	Vacuum pump
	Vacuum regulator
	Hose
	Reservoir

Circuit diagrams for all relevant vacuum components are available upon request.







Units and Symbols

Force

Parameter	Symbol	Unit in Numatics catalog
Length	l	mm, m
Width	b	mm, m
Height	h	mm, m
Diameter	d	mm, m
Volume	V	m^3, l

Weight

Parameter	Symbol	Unit in Numatics catalog
Mass	m	g, kg
Density	ρ	kg/m^3

Force

Parameter	Symbol	Unit in Numatics catalog
Force	F	N, kg x m/s^2
Theoretical holding force	F_{TH}	N
Acceleration	F_a	N
Tear-off force	F_A	N
Weight	G	N
Friction coefficient	μ	-

Time

Parameter	Symbol	Unit in Numatics catalog
Duration, evacuation time	t	ms, s, min, h
Speed	v	m/s
Acceleration	a, g	m/s^2, g

Temperature

Parameter	Symbol	Unit in Numatics catalog
Temperature	t	°C

Electrical magnetic values

Parameter	Symbol	Unit in Numatics catalog
Voltage	U	V
Strength of current	I	A

Vacuum values

Parameter	Symbol	Unit in Numatics catalog
Pressure, absolute	p	mbar, bar
Pressure difference	Δp	mbar, bar
Initial pressure	P_a	mbar, bar
Final pressure	P_e	mbar, bar
Negative pressure / vacuum	P_u	mbar, bar
Suction rate	V	l/min, m^3/h
Required suction rate	V_s	l/min, m^3/h
Nominal flow of sole-noid valve	V_v	l/min, m^3/h
Present suction rate of vacuum generator	V_{ve}	l/min, m^3/h
Total volume to be evacuated	V_g	m^3, l

Other information

Parameter	Symbol	Unit in Numatics catalog
Safety factor	S	-
Quantity of suction cups	n	-
Natural logarithm	ln	-
Noise level / sound pressure level	Lp	dB

Conversion Tables

Length

	m	ft	in
1 m	1.000	3.281	39.370
1 ft (foot)	0.305	1.000	12.000
1 in (inch)	0.025	0.083	1.000

Mass

	kg	lb	oz
1 kg	1	2.20	35.27
1 lb (pound)	0.45	1	16
1 oz (ounce)	0.03	0.06	1

Temperature

	K	ºC	ºF
1 Kelvin	1	-272.15	-457.87
1 ºCelsius	274.15	1	33.8
1 °Fahrenheit	255.93	-17.22	1

Suction rate

	m^3/ s	l/s	m^3/ h	l/min
m^3/s	1	1,000	3,600	60,000
l/s	10^{-3}	1	3.6	60
m^3/h	2.78×10^{-4}	0.278	1	16.67
l/min	1.67×10^{-5}	1.67×10^{-2}	0.06	1

Pressure

	bar	N/cm^2	kPa	mbar
1 bar	1	10	100	10^3
1 N/cm^2	0.1	1	10	100
1 kPa	0.01	0.1	1	10
1 mbar	10^{-3}	0.01	0.1	1

Volume

	m^3	cm^3	l
m^3	1	1×10^6	1,000
cm^3	1×10^{-6}	1	1×10^{-3}
l	1×10^{-3}	1,000	1

Vacuum ranges

	Absolute pressure in mbar	Mean free path of atoms*
Low vacuum	1,000 – 1	68 nm – 0,1 mm
Medium vacuum	$1 – 10^{-3}$	0.1 mm – 100 mm
High vacuum	$10^{-3} – 10^{-7}$	100 mm – 1 km
Ultra high vacuum	$< 10^{-7}$	> 1 km

Thread

Thread designation	External diameter in mm	Bead wire diameter	Pitch in mm
Metric ISO thread			
M3	3.00	2.5	0.50
M4	4.00	3.2	0.70
M5	5.00	4.1	0.80
M6	6.00	4.9	1.00
M8	8.00	6.6	1.25
M10	10.00	8.4	1.50
M12	12.00	10.1	1.75
Metric ISO fine thread		12.5	1.50
M14x1.5	14.00	14.9	1.00
M16x1	16.00	18.4	1.50
M20x1.5	20.00	28.4	1.50
M30x1.5	30.00		
Pipe thread			
G⅛	9.73	8.5	0.91
G¼	13.16	11.4	1.34
G⅜	16.66	14.9	1.34
G½	21.00	18.6	1.81
G¾	26.44	24.1	1.81
G1	33.25	30.3	2.31
G1¼	41.91	39.0	2.31
G1½	47.80	44.8	2.31
G2	59.61	56.6	2.31
G2½	75.18	72.2	2.31

Vacuum Glossary

Abrasion resistance
The abrasion resistance refers to the resistance of suction cups (elastomer part) against mechanical stress, especially friction. It is determined by the material properties of the suction cup as well as its shape.

Absolute pressure
The absolute pressure refers to the absolute zero point, or a space completely empty of molecules. In an absolute vacuum there is a pressure of 0 bar. A relative vacuum of -600 mbar corresponds to an absolute pressure of 400 mbar.

Air-saving function
Air-saving function refers to the ejector's air-saving function during the handling procedure. Once the ejector reaches a particular vacuum value, the evacuation process is interrupted. If the vacuum drops below a defined value, the ejector starts evacuating again. The air-saving function can therefore increase the energy and economic efficiency of a vacuum system.

Ambient pressure (atmospheric pressure)
Ambient pressure refers to the hydrostatic pressure that exists at any given point. Ambient pressure is also known as atmospheric pressure. The standard atmospheric pressure at sea level is 1,013 mbar. The ambient pressure drops with increasing altitude. The ambient pressure has a direct influence on the maximum vacuum value that can be reached.

Bernoulli's principle
Bernoulli's principle describes the drop in pressure of a fluid when it passes from a narrow section to a much wider section. In practice, this happens in the form of a direct transition into an open space. To prevent the vacuum collapsing, the fluid is diverted to the side.

Centralized vacuum system
In a centralized vacuum system, the vacuum is generated with a central vacuum source for more than one suction cups.

Check valve
The check valve is the valve that automatically monitors volume flow. If the volume flow exceeds a defined value, the valve closes automatically; for example, when suction cups are not being used.

Control pressure range
The control pressure range is the range between the lowest and highest permissible control pressures.

Cycle time
The cycle time refers to the time taken for a repetitive process to complete one cycle.

Decentralized vacuum system
In a decentralized vacuum system, a vacuum is generated directly at each individual vacuum suction cup. Positioning vacuum gene- ration directly at the suction cup allows for short pick-up and depositing times.

Evacuation time
The evacuation time refers to the time it takes to evacuate a certain volume to reach a required vacuum value.

Flow resistance
Flow resistance refers to a reduced flow cross-section in a vacuum line. The resistance reduces the volume flow that can pass through a line.

Friction coefficient
The friction coefficient [μ] refers to the relationship between friction force and normal force (contact force between suction cup and workpiece). The friction coefficient is not specified by an unit.

High vacuum
A high vacuum describes any vacuum in which there is an abso- lute pressure of 10-7 to 10-3 mbar. High vacuums are used, for example, in electron tubes and particle accelerators.

Holding force
Holding force refers to the force that can be exerted by a suction cup to grip a workpiece. It is calculated by multiplying the pres- sure difference by the effective suction area of the suction cup ($F = \Delta p \times A$). The holding force of a suction cup is thus influenced by underpressure and the suction area. It is a theoretical value, specified without safety factors. It is usual to state the holding force of a suction cup with a relative vacuum of 60%.

Hysteresis
Hysteresis refers to a pressure difference between two switching points, and thus defines the state of the output signal. The res- pective output signal changes when either the upper or lower limit value of the hysteresis is reached. Using the example of a vacuum switch: when the vacuum reaches a specified value, the signal changes to “ON”. If the vacuum drops below a defined value, the signal switches to “OFF”. Hysteresis is mainly used to control the air-saving function of ejectors.

Idle position of NC valve
The idle position of an NC valve refers to the position of the valve when it is not actuated, i.e. “closed” (normally closed).

Idle position of NO valve
The idle position of an NO valve refers to the position of the valve when it is not actuated, i.e. “open” (normally open).

Vacuum Glossary Continued

Inner volume
The inner volume indicates the volume of the body that has to be evacuated during a suction procedure. For example, the inner volume of a suction cup has an effect on the evacuation time.

Leakage
Leakage refers to a leak within the vacuum system. This can be caused by missing or faulty sealing elements, or by the porosity of the workpiece being processed.

Load case
Load case refers to the handling task, or the process of handling a workpiece.
Load case I – Suction cup horizontal, direction of force vertical
Load case II – Suction cup horizontal, direction of force horizontal Load case III – Suction cup vertical, direction of force vertical

Low vacuum
A low vacuum describes any vacuum in which there is an absolute pressure of 1 mbar up to atmospheric pressure (1,013 mbar). Examples of applications for a low vacuum include light bulbs and vacuum cleaners. Vacuum handling technology also uses values in the low vacuum range because these can be generated economically to create high suction power and short cycle times.

Medium vacuum
A medium vacuum describes any vacuum in which there is an absolute pressure between 0.001 mbar and 1 mbar. Medium vacuums are used, for example, in low-pressure gas-filled lights.

Nominal flow
Nominal flow refers to the maximum flow through a certain diameter (nominal diameter). The nominal flow is given in l/min or m3/h.

Normal force
Normal force is the force component acting perpendicular to a surface. Every force acting on a surface can be divided into normal force and shear force (see “Shear force”). Based on the normal force, the friction force can be calculated using the friction coefficient for a material pairing. The result indicates the friction force between two surfaces, for example between a suction cup and a workpiece. Normal force is measured in Newton [N].

NPN – Switching output
NPN switching output refers to the configuration of a switching output in cases where the load is connected to the positive pole of the operating voltage source. The output transistor of the vacuum switch connects the active device through to the opera- ting voltage, allowing current to flow through the consuming device.

Minimum radius of curvature
The minimum radius of curvature refers to the smallest radius that a suction cup can securely grip. For round suction cups, this refers to a sphere, while for oval suction cups it refers to a cylinder.

Operating temperature
The operating temperature is the temperature range in which a product can be deployed or run.

Overpressure resistance
Overpressure resistance refers to the maximum pressure that a body (for example, a reservoir or vacuum filter) can resist.

PNP Switching output
PNP switching output refers to the configuration of a switching output in cases where the load has a permanent connection to the operating voltage source. The output transistor of the vacuum switch connects the active device to the positive pole, allowing current to flow through the consuming device.

Recovery time
The recovery time is the period in which the product is not being used or is not subject to significant work loads. The product can recover during this time.

Reference pressure
Reference pressure is the pressure referred to by a sensor. Vacuum switches, for example, have a connection for reference air.

Relative pressure
Relative pressure refers to the value of pressure in relation to the prevalent ambient pressure. The vacuum is given using negative values. Relative pressure has a pressure of 0 mbar as a reference point. An absolute pressure of 400 mbar corresponds to a relative pressure of -600 mbar. In the field of vacuum handling, it is also common to state the values in percentages:
-600 mbar corresponds to a vacuum of 60%.

Reversing valve
A reversing valve is a type of changeover valve used in a blower. The valve supplies the system alternately with overpressure and underpressure. The valve thus controls the suction, blow-off and neutral setting in the vacuum system.

Shear force
Shear force is the force acting tangentially to a surface and indicates how much friction can be transferred between the suction cup and workpiece. Shear force is given in Newton [N].

Vacuum Glossary Continued

Standard liter
A standard liter is the measurement of a gas occupying a liter at 20 °C and 1,013 mbar (standard state).

Standard pressure
Standard pressure is the pressure in the atmosphere under stan- dard conditions. In both technology and the natural sci- ences, this is 1,013 mbar at 0°C. The values in the Numatics catalog refer to a temperature of 20 °C

Standard temperature
Standard temperature is the temperature under standard condi- tions. The values in the Numatics catalog refer to a temperature of 20 °C.

Suction force
See "Holding force"

Suction cup stroke
The suction cup stroke refers to the stroke effect that is created by the suction cup when picking up a workpiece. The stroke value indicates the maximum contraction of the suction cup.

Suction power
See "Suction rate"

Suction rate
Suction rate refers to the suction power of a vacuum genera- tor. This value indicates the volume that can be evacuated by a vacuum generator in a certain time. The suction rate is given in l/min or m3/h.

Switching point
The switching point refers to a point at which a switch changes the state of the output signal. If, for example, a programmed vacuum value is reached on a vacuum switch, the output signal switches to "ON" and there is voltage at the switch output.
The initial position of the signal can be set to either NC (opener) or NO (closer).

Vacuum
A vacuum is a pressure range lower than that of the ambient pressure. The vacuum value is divided into various classes; refer to "High Vacuum", "Medium Vacuum" and "Low Vacuum".

Ventilation time
The ventilation time refers to the time it takes to dissipate vacuum in a system. This defines the time it takes to release a workpiece. The ventilation of a suction cup can take place either atmospheri- cally or actively by a compressed air pulse (active blow off).

Venturi principle
The Venturi principle describes the correlation between dynamic and static air pressure when air flows through a tube. At the narrowest section, the dynamic pressure is at a maximum, while the static pressure is at a minimum. Since the same volume is flowing through the tube, the velocity increases in proportion to the cross sections. Because of this differential pressure, a vac- uum can be created and air can be drawn in by using Venturi nozzles with a side inlet port. Vacuum generators based on this principle are called ejectors.

Volume flow
Volume flow refers to the volume of a medium that flows through a cross section within a certain amount of time.

Workpiece temperature
The workpiece temperature is the temperature of a processed workpiece. This temperature can influence the selection of a suitable suction cup material.