CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

Department of Instrumentation and Control Engineering

Partial Vacuum Application for Manipulating Workpieces

BACHELOR THESIS

2021

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Partial Vacuum Application

for Manipulating Workpieces

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Guidelines:

1. Study properly the didactic material related to the vacuum technique TP230
2. Study properly software FluidSIM – mainly vacuum, electropneumatic and GRAFCET libraries
3. Implement basic tasks for catching and manipulating with worpieces using the clasical electropneumatics
4. Implement basic tasks for catching and manipulating with worpieces using the virtual PLC programmed by GRAFCET language

Bibliography / sources:

[1] Software FluidSIM, Festo Didactic
[2] Vacuum technique, TP230, Festo Didactic
[3] Piab gripping, lifting and moving solutions - piab.com. Available on: https://www.piab.com/.

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III. Assignment receipt

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Declaration

I confirm that the diploma (bachelor's) work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of the documents and literature.

In Prague ………………   ……..……………………………….

Name and Surname

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I would also like to extend my utmost appreciation towards my parents who worked very hard to get me where I am now, I will never forget everything they did for me, and I hope to always make them proud to the best of my abilities.

Abstract

The information and work in this document is focusing on understanding how does vacuum technology work and how it is used to manipulate workpieces. The program used to simulate the matter at hand will be introduced and the key words regarding the topic of vacuum technology will be defined to be able to understand the tasks in the practical part of this document. It will also be seen what parts can be used to make the processes descried in the tasks more efficient, more secure, and ultimately more cost effective which are all important parameters for any sector. Finally, within the final task of the practical part of this document it will be seen how vacuum technology is applied in handling and manipulating workpieces while understanding the reasoning behind why and how it works.

Keywords: Pneumatics, Electropneumatics, Vacuum technology, FluidSIM, Virtual PLC, GRAFCET, Workpiece manipulation

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Chapter 1

1.1 Introduction to Applications of Vacuum in Handling Technology

Vacuum technology is a method used to evacuate air from a closed volume by creating a pressure differential from the closed volume to usually the open atmosphere, this technology revolves around pressure. There are many industries that take advantage of vacuum technology to handle its requirements, and many of them use the instruments of FESTO and piab companies which are among the top companies applying vacuum technology especially in handling workpieces. The company piab lists the following industries (1):

- Additive Manufacturing
- Automotive
- Chemical
- Food & Beverage
- Logistics & Warehousing
- Packaging
- Pharmaceuticals
- Plastics

Taking a look at the automotive, and packaging industries should suffice in illustrating how vacuum can be applied to handle workpieces. So, taking a look at the automotive industry in the piab webpage, it is displayed how vacuum technology is used for handling a car door for final assembly in *Figure.1*:

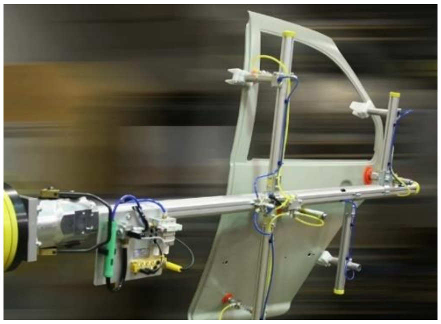


Figure 1. Door on/off ergonomic tools (2)

Another application of vacuum technology within the automotive industry is the press transfer of metal sheets in the final assembly process as displayed in *Figure.2*:

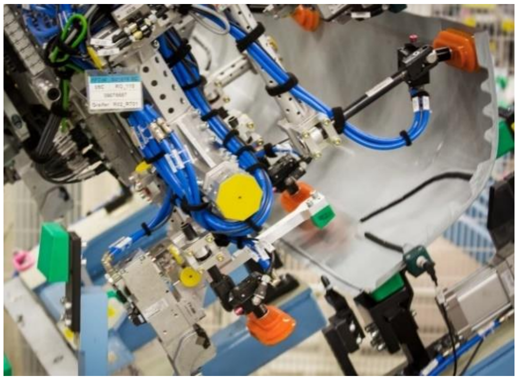


Figure 2. Press transfer of metal sheets (3)

Moving to the packaging industry, vacuum technology is useful and efficient in handling boxes and containers as displayed in *Figure.3*:

Figure 3. Handling Boxes and containers (4)

1.2 Basic Terminology

Pressure is defined as the quotient of a normal force on a surface area. The official unit of pressure is Pascal $[Pa]$ which is equivalent to $[\frac{N}{m^2}]$, of course another unit can be used to represent pressure such as $[bar]$ which will be used in the practical part of this document.

$$p = \frac{F_N}{A}$$

Equation 1. Pressure relation (5)

$p \ldots pressure$

$F_N \ldots normal\ force$

$A \ldots surface\ area$

Vacuum is officially defined as the state of a gas with the density of its molecules less than the density of the molecules in the atmosphere at the surface of the earth. Now this is the definition that is used as we measure, experiment, work with, or monitor pressure; However, it must be noted that this is what may be referred to as possible vacuum or practical vacuum, and this concept comes from the notion of ideal vacuum which in vacuum technology is defined as a closed volume with the density of the gas inside equal to 0.

Standard State is an important basic term describing the state of matter (solid/liquid/gas) under standard conditions. Standard conditions represent both a standard temperature and a standard pressure. Standard temperature being 273.15 Kelvin or 0 degrees Celsius, and standard pressure being 101,325 Pa or 1.01325 bar at sea level.

The tendency is to use Pascal $[Pa]$ in scientific circles however in vacuum technology the tendency is to use the unit millibars $[mbar]$.

The dependance of the pressure on the altitude from sea level can be observed through *Figure.4*:

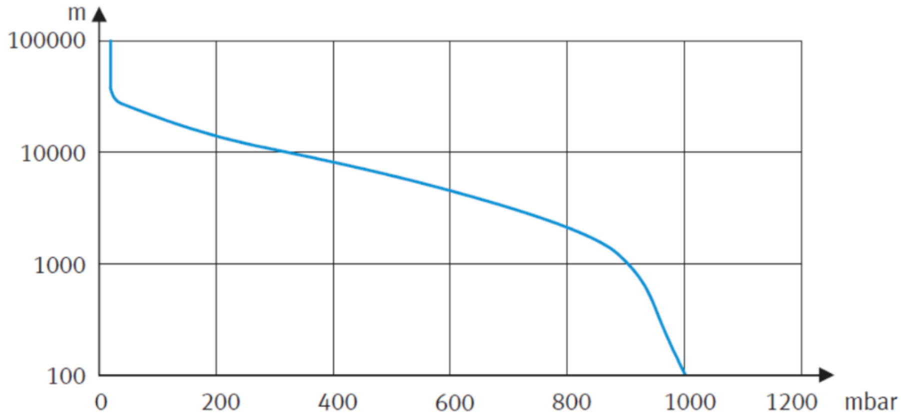


Figure 4. Ambient atmospheric pressure at various altitudes above sea level (5)

This graph is important to be able to recognize that the pressure that is dealt with is different depending on where the position is with respect to sea level due to the dependance of the ambient atmospheric pressure dropping the higher the position is and approaching 0 according to the graph close to 100,000 m above sea level. Usually, the application at study in this document tends to be within the range of 0 m to 2000 m with respect to sea level, which has a linear dependance describing that the ambient pressure drops by approximately 1% per 100 m of altitude increase. What this means is that a lift suction cups that are meant to carry a certain load at sea level will not be able to carry the same load the higher the position is according to sea level. A simple and effective way to know how much could be carried at a certain altitude would be:

$$m = m_{limit} * [\left(100 - \frac{y}{100} \right) * \frac{1}{100}]$$

Equation 2. Mass that a suction cup can carry relation (5)

m ... $mass\ that\ suction\ cup\ can\ carry$

m_{limit} ... $limit\ mass\ that\ suction\ cup\ can\ carry\ at\ sea\ level$

y ... $altitiude\ above\ sea\ level$

Units to be used are $[Kg]$ for the masses (m and m_{limit}) and $[m]$ for the altitude (y).

Evacuation time is a very important term in vacuum technology, and it represents the time required by a vacuum generator or any vacuum device to generate the desired degree of vacuum.

1.3 Ranges of Vacuum

A set of vacuum ranges must be defined and which of these ranges does the application at study works within. To help visualize the vacuum range, the *Figure.5* aims to show the different ranges in a figure form, and *table.1* is the tabulated version of *Figure*.5:

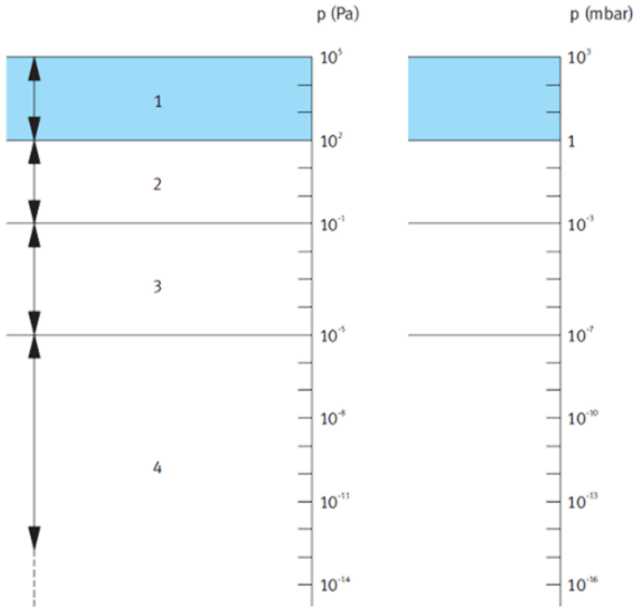


Figure 5. Vacuum Ranges (5)

Vacuum range	Absolute Pressure $[Pa]$	Relative Pressure $[mbar]$
1. Low vacuum	$10^5 - 10^2$	$10^3 - 10^0$
2. Medium high vacuum	$10^2 - 10^1$	$10^0 - 10^{-3}$
3. High vacuum	$10^{-1} - 10^{-5}$	$10^{-3} - 10^{-7}$
4. Ultra-high vacuum	$10^{-5} - 10^{-14}$	$10^{-7} - 10^{-16}$

Table 1. Vacuum range (5)

In handling technology, the tendency is to work within the low vacuum range which is highlighted in *table.1* with 1000 mbar to 1 mbar of absolute pressure or we can look at it as -0.001 bar to -0.999 bar of partial vacuum. Notice how a minus sign is before the relative pressure because this is how partial vacuum is represented, as the negative value of the relative pressure.

Energy demands are very important and should be studied to know what level of partial pressure should be aimed for to satisfy the predetermined set of needs and minimize cost coming through as energy demand.

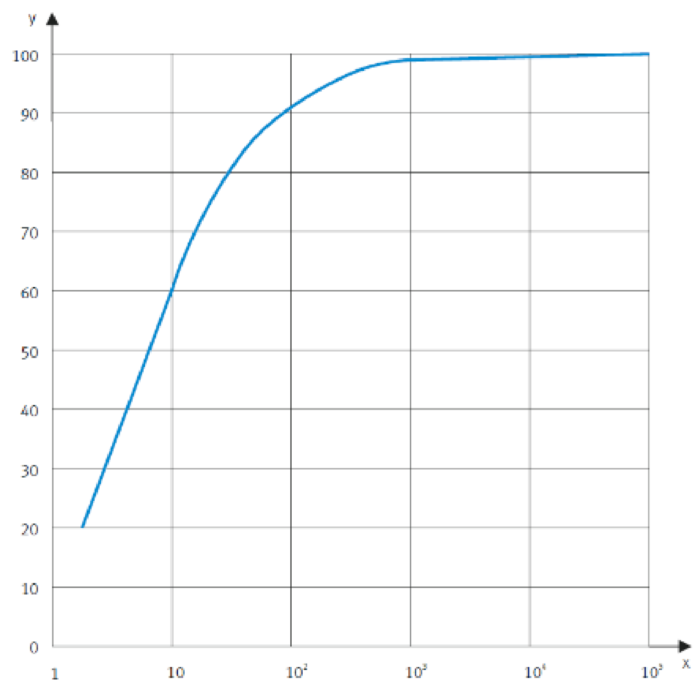


Figure 6. Energy Demand at Negative Pressure (5)

Where y represents vacuum percentage and x represents energy demand factor. It can be seen that the energy demand rises drastically by almost 10 times after 90% vacuum attained, it can also be seen that the energy demand is doubled from 60% to 90% vacuum while the vacuum is increased by just 50%. Statistical analysis of practices regarding evacuation time measurement showed that the evacuation time can triple within these conditions. Now it must be assessed how impactful is it for the desired work, is it worth it to supply twice the energy to get 3 times slower evacuation time and stronger holding force? Or is it better to spend less resources, consume less energy, and have a 3 times faster evacuation time at the expense of a weaker holding force?

Most tend to agree that 60% vacuum is to be considered as a practical reference value due to how it needs significantly less energy to perform adequately.

1.4 Vacuum Generation and Selection Parameters for Pumps and Ejectors

Now that a sufficient foundation of some of the most important terms in vacuum technology has been established, the conversation about how vacuum is generated is brought forward, so basically there are two processes by which a vacuum is generated:

1. Using pumps
2. Using ejectors

The concept at work in both processes is the same, which is to reduce the pressure within the closed volume of the suction cup. The key difference is that ejectors use compressed air to generate the vacuum whereas pumps tend to use electricity to generate the vacuum.

Displacement pumps are the most common vacuum pumps and are defined as mechanical pumps which draw in the gas to be delivered with the help of mechanical components such as a piston, rotor, slides, etc. These pumps have two modes of operation:

1. Oscillating displacement pumps
    - Reciprocating pumps
    - Diaphragm pumps
2. Rotary displacement pumps
    - Rotary vane pumps
    - Lobe pumps

The pumping chamber inside the pump is periodically being enlarged and reduced throughout the pumping process, when it is expanded to its maximum capacity then the volume of the pumping chamber is called the suction volume.

In the next page reciprocating pumps and rotary vane pumps will be discussed to get the basic understanding of the key differences between oscillating and rotary displacement pumps.

Reciprocating pumps have a piston that moves up and down hence the oscillating mode, the suction chamber volume changes as a consequence of that movement. It is an easy concept to digest when looking at the cutaway view of the pump in *Figure.7*:

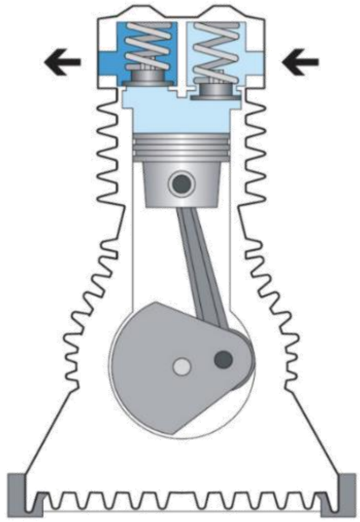
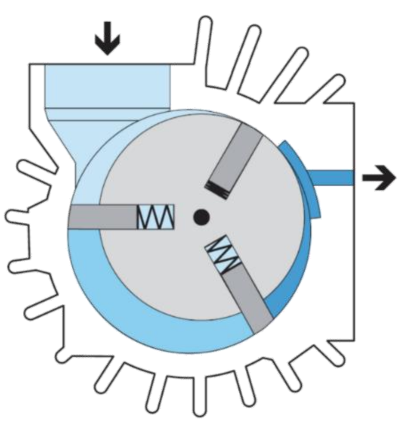


Figure 7. Reciprocating pump cutaway view (5)

When the piston moves down and the suction chamber volume is expanded that is when suction occurs, and when the piston moves up the suction chamber volume is shrunk, and it is when compression and ejection occur. This type of pump has the advantage of being very simple to understand while carrying out its function.

Moving on to rotary vane pumps which are more common and have a rotating motion causing the vacuum rather than an oscillating one. The cutaway view in *Figure.8* will help in understanding how the vacuum is generated:



It can be seen how the pumping chamber is changing its volume with time from the biggest volume (the area in light blue) to a smaller volume (the area in sea blue) and finally to the smallest volume in the pump (the area in dark blue) that is where the compression/ejection happens.

Figure 8. Rotary slide-valve pump cutaway view (5)

Now that some footing in the matter of pumps, their modes, and how they operate has been established, the listing of the parameters that must be taken into consideration when selecting a pump for whatever application we need arises. The list of parameters is as follows:

1. Suction capacity $[\frac{m^3}{h}]$ in standard conditions
2. Final pressure $[mbar]$
3. Evacuation time $[s]$
4. Pump motor power $[KW]$
5. Noise $[dB]$
6. Operating temperature $[°C]/[K]$

Different manufactures will use a different design or oil coating or material in manufacturing their pumps so one must always check their catalogues for the relevant graphs and data to make a correct and well-informed decision on which pump to buy and from who.

Departing from pumps, ejectors are approached which also generate vacuum but using compressed air to do so. The main principal piloting ejectors is the venturi principle that is when a fluid flowing through a constricted section of a tube undergoes a decrease in pressure (6). The cutaway view of an ejector is in *Figure.9* to help in visualizing it:

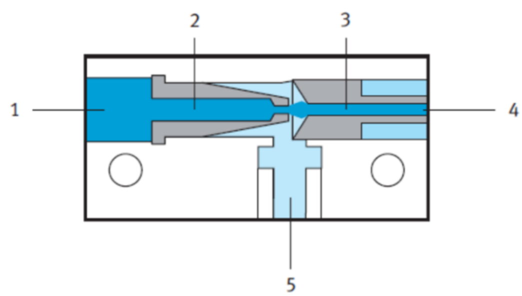


Figure 9. Single stage ejector cutaway view (5)

1 … Supply port

2 … Jet nozzle

3 … Collector nozzle

4 … Exhaust

5 … Vacuum port

The way that the vacuum is created when using ejectors is by the compressed air flowing through the supply port into the jet nozzle where the velocity of the air increases substantially to ultrasonic speeds due to the change in the cross-section area of the tube, when the air exits the jet nozzle, the air expands and flows into the collector nozzle. It is at that stage that the vacuum starts happening around the jet nozzle, because air is being drawn in through the vacuum port.

There are types of ejectors out in the market so distinguishing single stage and multi-stage ejectors is a good first step. Typically, single stage ejectors reach to about -0.9 bar of negative pressure, while multi-stage ejectors can reach to -0.99 bar. When an ejector has more than one function then it is referred to it as a compact ejector because it takes care of more than one function in a single package which makes it easier for the assembly and reduces planning of how to implement other functions using different components while considering compatibility.

The *Figure.9* describes a basic single stage ejector which is also referred to as a vacuum generator. And to take a look at an example of a compact ejector, the *Figure.10* will show a cutaway view of a single stage ejector with repulsion function:

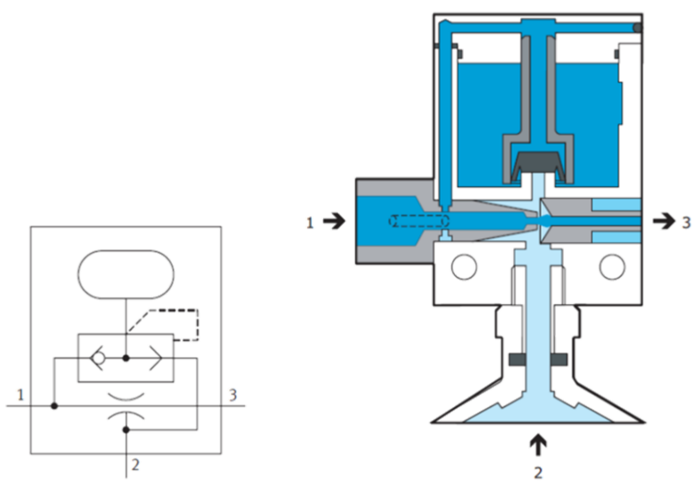


Figure 10. Single-stage ejector with repulsion function (compact ejector) cutaway view (5)

This particular ejector is made so that when the supply is stopped the stored air in the reservoir is vented through the quick exhaust and in doing so it repels the workpiece from the suction cup.

The drawing to the left in *Figure.10* is how it would be displayed in the program FluidSIM® that will be used for the practical part which will be introduced in *subchapter 1.6*.

Multi-stage ejectors are not far off from single stage ejectors due to the fact that they are composed of multiple single stage ejectors connected in series. The concept is very much the same as single stage ejectors, but multi-stage ejectors use valve flaps that can be seen in *Figure.11* that is a cutaway view of a multi-stage ejector:

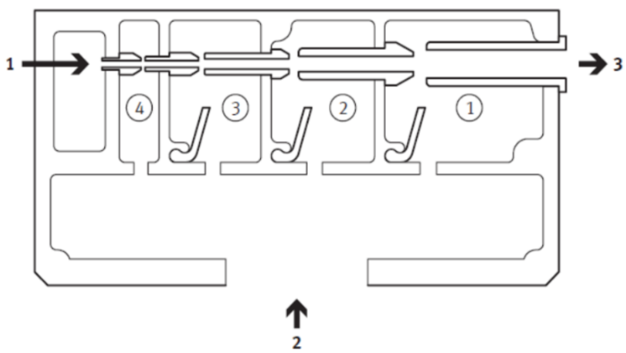


Figure 11. Multi-stage ejector cutaway view (5)

As the negative pressure is increased, the valve flaps seen in *Figure.11* would close in the order of 1 2 3 due to the fact that the three flaps are not identical and react to different negative pressures.

Compact ejectors are really useful and versatile for they do not only act as ejectors but also as any of the following and more:

- Control valves
- Silencers
- Filter
- Non-return valve
- Flow control valve

Similar to pumps the listing of parameters which should influence the selection of ejectors should be made, these parameters would be:

1. Suction capacity $[\frac{l}{min}]$ relative to the operating pressure
2. Suction capacity $[\frac{l}{min}]$ relative to the negative pressure
3. Negative pressure relative to operating pressure
4. Air consumption relative to operating pressure
5. Noise level relative to operating pressure
6. Evacuation time $[sec]$
7. Peak pressure of the exhaust pulse for ejectors with repulsion function
8. Efficiency relative to vacuum at a defined operating pressure
9. Tubing volume based on tubing length and diameter
10. Suction cup volume based on suction cup size and number

1.5 Suction Cups, Selection of Suction Cups and Vacuum Security Valves

The term suction cups have been stumbled upon a bunch of times so far and it is about time that a deeper study about it must be made. Suction cups are very important especially in handling technology because it is an efficient and cost-effective way to handle a spectrum of work pieces ranging from very light workpieces to really heavy ones even in the range of hundreds of kilograms. There are different types of suction cups that are made from different materials tailored to the work demands, materials like PUR (polyurethane), FPM (fluoroelastomer), NBR (nitrile rubber), and Si (silicon). The function of suction cups is to attach to a surface (the surface of the workpiece in our application) by having lower pressure in the suction cup volume than ambient pressure. Suction cups are typically directly connected into the ejector, to create the partial vacuum which generates the holding force that grips the workpiece. The greater this partial vacuum is the greater the holding force, this relation has to be provided by the manufacturer.

To dive a bit deeper it must be understood that what the manufacturer will provide as the theoretical holding force is not the actual usable holding force that will be attained when using that specific suction cup, because what really matters is the so called effective holding force which is significantly less than the theoretical holding force due to factors that are not factored in when calculating the theoretical holding force such as the deformation of the suction cup or the flexing of the workpiece which does impact the holding force greatly. The actual/usable/effective holding force is actually about 50% of the provided theoretical holding force and that is what must be considered to avoid problems in this study's application, which translates to using a $factor\ of\ safety\ =\ 2$, however this is for the typical case of the effective holding force acting perpendicularly to the suction surface but when the effective holding force is used parallel to the suction surface the factor of safety must be adjusted to $factor\ of\ safety\ =\ 4$. Taking this up a notch one could also say that it is possible to increase the factor of safety more due to minimal static friction, but it's not something that one would encounter a lot.

In cases where workpieces that are easily deformed or are really thin, multiple suction cups must be used across the whole surface of the workpiece. Taking a look at the cutaway view of flat suction cups (*Figure.12*) and bellows suction cups (*Figure.13*):

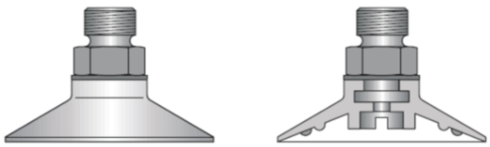


Figure 12. Flat suction cup (5)

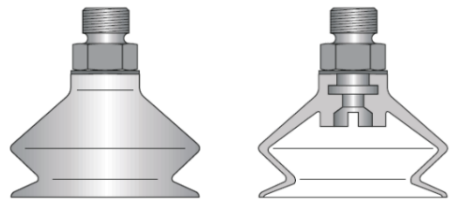


Figure 13. Bellows suction cup (5)

Now that a sense of familiarity with suction cups has been reached, the next step becomes knowing how to select the appropriate suction cup for the application. The crucial input parameters that are needed are the weight of the workpiece and the vacuum pressure provided. In *page.14* the derivation of the equation to find the effective suction cup diameter will be articulated.

From the rearrangement of *equation.1* we attain the force relation with pressure in *equation.3*:

$$F = A * p$$

Equation 3. Force relation with pressure

From basic geometry it is common knowledge that the area of a circle is defined in *equation.4*:

$$A = \pi * \frac{d^2}{4}$$

Equation 4. Area of a circle formula

d ... theoretical suction cup diameter $[mm]$

From basic physics it is known that force has a relation with mass and acceleration as in *equation.5*:

$$F = m * a$$

Equation 5. Force relation with acceleration

$m \dots load\ mass\ [kg]$

$a \dots acceleration\ \left[\frac{m}{s^2}\right]$

So, what is needed is to plug in the following variables in *equation.6*, the vacuum pressure given into p, the mass of the workpiece into m and gravitational acceleration into a. Finally, equating *equation.3* with *equation.5* results in the formulation of *equation.6*:

$$F = \pi * \frac{d^2}{4} * p = m * a$$

Equation 6. Equating force with pressure and with acceleration

With $a = g = 9.81 \left[\frac{m}{s^2}\right]$, where g is the gravitational acceleration

The final algebraic rearrangement of *equation.6* gives the theoretical suction cup diameter as displayed in *equation.7*:

$$d = \sqrt{\frac{4mg}{\pi p}} = 3.53\sqrt{\frac{m}{p}}$$

Equation 7. Suction cup diameter formula

Please note that *equation.7* works for vacuum pressure in $[Pa]$ and mass in $[Kg]$ to output the theoretical suction cup diameter in $[m]$. If the desired equation is one that immediately gives out the value in $[mm]$ then use *equation.8*:

$$d = 11.2\sqrt{\frac{m}{p}}$$

Equation 8. Suction cup diameter formula without factoring in the factor of safety (5)

By this point it must be realized that what was done was theoretical and without consideration of deformations or any of the other issues that were discussed earlier and so the safety factor must be applied to *equation.8* to have the relation that must be used to select which suction cup will be used as shown in *equation.9*:

$$d = 11.2\sqrt{\frac{mk}{p}}$$

Equation 9. Suction cup diameter formula factoring in the factor of safety (5)

$k \ldots factor\ of\ safety$

While selecting the suction cups it must be made sure that vacuum values are not high because as it is known from the relations mentioned in *page.13* and *page.14* that if pressure is increased, more loading force will exist, and it will cause the wear of the suction cup which is not ideal. When a satisfactory vacuum pressure value is achieved without overshooting, the service life of the suction cup is reduced which ultimately saves money, of course this is not the only way that this saves money but also it will require less energy to have this satisfactory level of vacuum rather than overshooting it as we learned from *page.6*.

Going from -0.6 bar to -0.9 bar will increase the force by 50% and the energy demand by 10 times which is a lot of resources and cost. If more force needs to be generated at the suction cup then a more efficient way than increasing the vacuum is to just increase the effective diameter of the suction cup since the area is directly proportional to the force, this also has the benefit of a shorter evacuation time which could shorten the cycle time in the desired application saving valuable time and the ability to work more workpieces than if high vacuum levels were used.

Suction cup material is an important factor or parameter in the selection of which suction cup to use because it could provide the information of how likely it will survive with the level of vacuum at hand and also how resistant to chemicals is it, being mindful of that while making the selection can help in reducing the expenses on maintenance and also make the interval between maintenance sessions longer which ultimately results in more work, less down time, and less cost.

There are a handful of things to consider when deciding on suction cups for handling workpieces:

- How much vacuum pressure do is desired?
- Number of suction cups that will be used
- Are special cups for the workpieces needed or are the standard ones sufficient?
- The acceleration of the motion the workpiece will go through
- The trajectory of the workpiece with respect to the suction surface

These aren't the only considerations but for the next section the desire is to highlight the second bullet point which is the number of suction cups that will be used, because it would be an issue if a failure happens at one of the suction cups that are connected to the same vacuum generator. That issue would be the whole vacuum pressure collapsing, so to prevent that a valve called vacuum security valve or vacuum efficiency valve is used. This valve is installed between the vacuum generator and the suction cup so that if any issue or failure occurs the vacuum security valve will automatically stop the flux of air. Taking a look at *Figure.14* one can see how this valve looks like and how it is drawn in FluidSIM®:

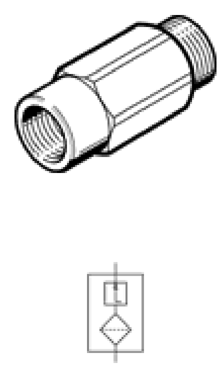


Figure 14. Vacuum security valve (7)

In *Figure.15* the connection between the vacuum generator and the multiple suction cups is displayed as it is on the program FluidSIM®.

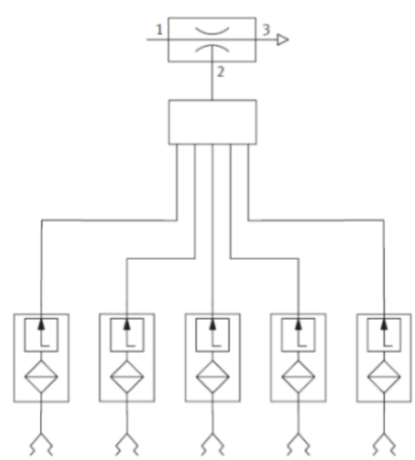


Figure 15. FluidSIM® representation of vacuum security valves connections (5)

The cutaway view of vacuum security valves is displayed in *Figure.16*:

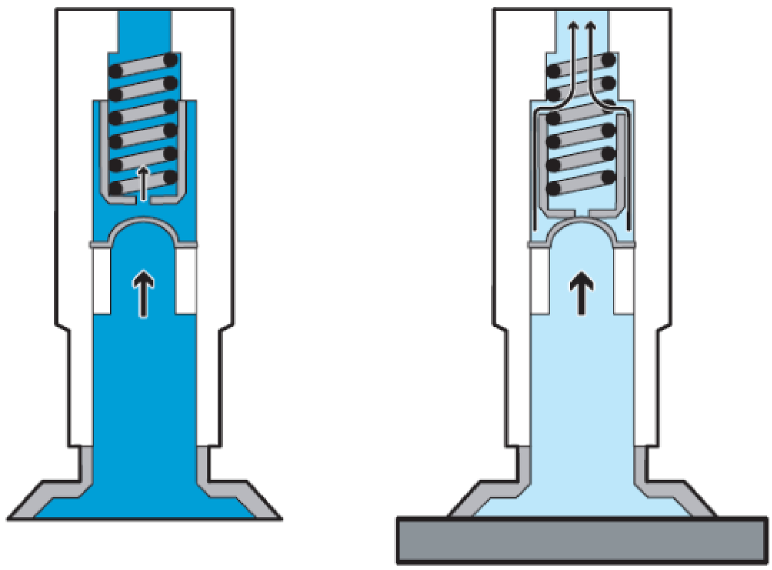


Figure 16. Vacuum security valve cutaway view (5)

Figure.16 describes two situations, when the workpiece is gripped (right) and when the workpiece isn’t gripped for whatever reason (left). If the suction cup is exposed to the environment the float is going to press up against the housing due to the partial vacuum and so the air can only flow through a small hole which will greatly reduce its flowrate (the situation on the left), and if the workpiece is properly contacted with the suction cup then air flow is reduced causing the spring to push the float down which will generate a full vacuum because now air flows around the float.

To stratify the steps in selecting the suction cups, the material “2000 options, 1 principle, zero selection problems” from the company FESTO (8) can be used. The material displays five clear steps that one must go through in selecting suction cups. It is always useful to have a path that is ordered in order to minimize any issues or neglections. In the next pages the steps will be listed and explained in order.

1. Calculating the weight of the workpiece

$$m = L * W * H * \rho = V * \rho$$

Equation 10. Weight of the workpiece formula (8)

$m \ldots weight\ of\ the\ workpiece\ [g]$

$L \ldots length\ [cm]$

$W \ldots width\ [cm]$

$H \ldots height\ [cm]$

$\rho \ldots density\ [\frac{g}{cm^3}]$

$V \ldots volume\ \ [cm^3]$

2. Selecting suction cup shape

The suction cup shape must be chosen depending on the surface of the workpiece that will be handled so the following categories arise:

- Standard suction cups: for flat surfaces mainly such as metal sheets or cardboard

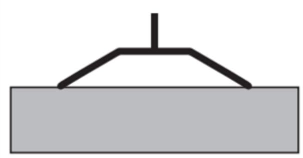


Figure 17. Standard suction cups (8)

- Extra deep suction cups: for round workpieces

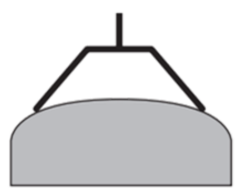


Figure 18. Extra deep suction cups (8)

- Bellows suction cup with 1.5 convolutions: for beveled surfaces and pliable/flexible workpieces

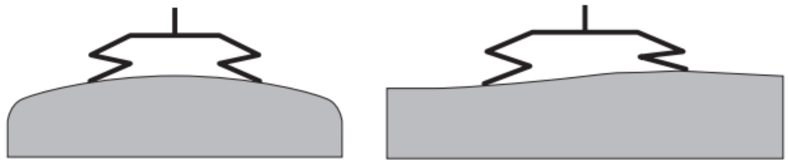


Figure 19. Bellows suction cups with 1.5 convolutions (8)

- Bellows suction cup with 3.5 convolutions: for delicate workpieces like glass bottles or light bulbs.

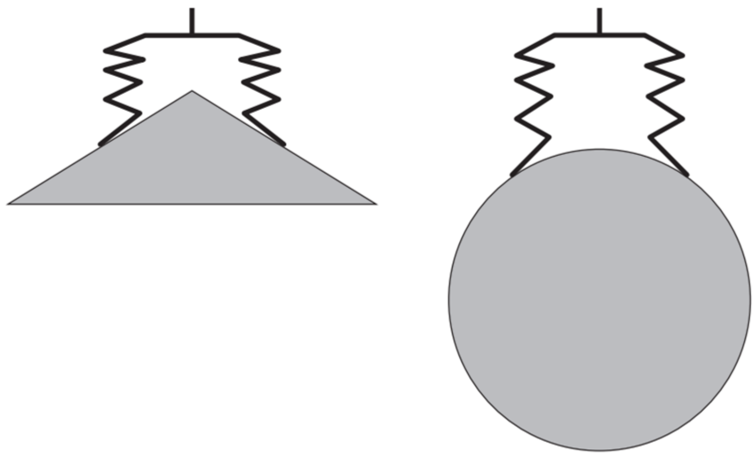


Figure 20. Bellows suction cups with 3.5 convolutions (8)

- Oval suction cup: for slim oblong workpieces like pipes

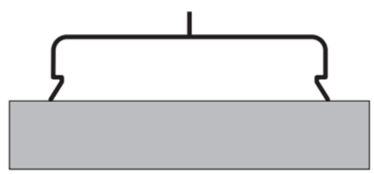


Figure 21. Oval suction cup (8)

3. Calculating the retention and breakaway forces

Calculating the retention forces using the weight of the workpiece and acceleration is required, there are three cases for this, and each has its own calculating formula appropriate for the orientation of the workpiece and direction of the movement:

- Case 1: Horizontal suction cup position with vertical movement

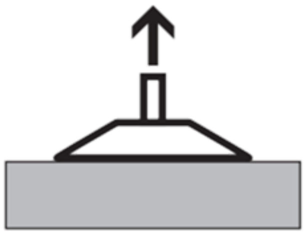


Figure 22. Horizontal suction cup position with vertical movement (8)

Calculation Formula for case 1:

$$F_H = m * (g + a) * S$$

Equation 11. Retention force (horizontal suction cup position with vertical movement) (8)

- Case 2: Horizontal suction cup position with horizontal movement

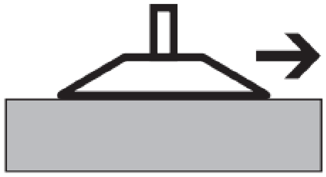


Figure 23. Horizontal suction cup position with horizontal movement (8)

Calculation Formula for case 2:

$$F_H = m * \left(g + \frac{a}{\mu}\right) * S$$

Equation 12. Retention force (horizontal suction cup position with horizontal movement) (8)

- Case 3: Vertical suction cup position with vertical movement

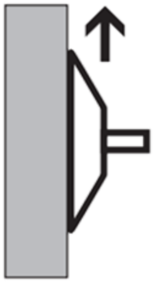


Figure 24. Vertical suction cup position with vertical movement (8)

Calculation Formula for case 3:

$$F_H = \left(\frac{m}{\mu}\right) * (g + a) * S$$

Equation 13. Retention force (vertical suction cup position with vertical movement) (8)

$m \ldots weight\ of\ the\ workpiece\ [Kg]$

$F_H \ldots theoretical\ retention\ force\ of\ suction\ cup\ [N]$

$g \ldots gravitational\ acceleration\ [\frac{m}{s^2}]$

$a \ldots acceleration\ of\ the\ system\ [\frac{m}{s^2}]$

$S \ldots safety\ factor\ (= 1.5\ for\ vertical\ and\ horizontal\ movement,$

$= 2\ for\ rotational\ movement)$

$\mu \ldots friction\ coefficient\ (= 0.1\ for\ oily\ surfaces, = 0.2\ to\ 0.3\ for\ wet\ surfaces,$

$= 0.6\ for\ rough\ surfaces, and$

$= 0.5\ for\ wood\ metal\ glass\ and\ stone)$

4. Determination of suction cup diameter and shape

In this section the concepts attained from *page.13* and *page.14* are used, however FESTO provides a standardized sheet for this selection which takes into consideration the retention force at -0.7 bar:

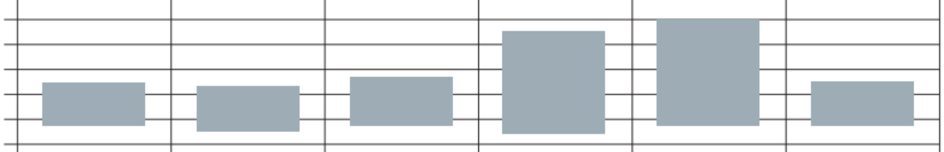
Suction cup round	F_A at –0.7 bar					Suction cup oval	F_A at –0,7 bar
							
Suction cup-Ø [mm]	Standard	Extra deep	1.5 convolution bellows	3.5 convolution bellows	Suction cup, bell-shaped	Suction cup size [mm]	oval
2	0.10 N					4 x 10	2.0 N
4	0.46 N					4 x 20	3.4 N
6	1.10 N					6 x 10	2.9 N
8	2.30 N					6 x 20	5.9 N
10	3.90 N		4.7 N	3.9 N		8 x 20	8.0 N
15	8.50 N	9.8 N				8 x 30	10.9 N
20	16.30 N	17.0 N	12.9 N	8.2 N		10 x 30	15.2 N
30	40.80 N	37.2 N	26.2 N	20.8 N	36 N	15 x 45	32.0 N
40	69.60 N	67.6 N	52.3 N	42.4 N	64 N	20 x 60	62.8 N
50	105.80 N	103.6 N	72.6 N	63.4 N	97 N	25 x 75	92.5 N
60	166.10 N	162.5 N			134 N	30 x 90	134.4 N
80	309.70 N	275.0 N	213.6 N		245 N		
100	503.60 N	440.8 N			375 N		
150	900.00 N						
200	1610.00 N						

Table 2. Suction cup diameters depending on suction cup shape and retention force (8)

5. Observing of environmental conditions

This step allows for the selection of the material of the suction cup depending on the environment and the material of the workpiece it is trying to grip, FESTO also provides a standardized sheet that highlights operating temperatures, typical applications, material resistances, etc. to help in making a well-informed decision in this final step:

Material	Nitrile rubber	Polyurethane	Vulkollan®	Silicone	Fluor rubber	Nitrile rubber (anti-static)
Charakteristic operating temperatures in °C	−10 … +70	−20 … +60	−10 … +80	−30 … +180	−10 … +200	−10 … +70



Material characteristics	Nitrile rubber	Polyurethane	Vulkollan®	Silicone	Fluor rubber	Nitrile rubber (anti-static)
Material Code	N	U	T	S	F	NA
Colour	Black	Blue	Red-brown	Transparent	Grey	Black with white dot
Wear resistance Abrasion resistance	••	•••	•••	•	••	••
Shore hardness A	50 ±5	60 ±5	72 ±5	50 ±5	60 ±5	50 ±5
Typical application areas	Conventional application	Rough surface	Automobile industry	Food industry	Glass industry	Electronics industry
Very demanding conditions	–	•	•	•	–	–
Food	–	–	–	•	–	–
Oily workpieces	•	•	•••	–	•	•
High ambient temperatures –	–	–	•	•	–	
Low ambient temperatures –	•	•	•	–	–	
Smooth surfaces (glass)	•	•	•	–	•	–
Rough surfaces (wood, stone)	–	•	••	–	–	–
Anti-static	–	–	–	–	–	•
Fragile surfaces	–	•	•	•	–	–
Resistance						
Atmospheric conditions	•	••	••	•••	•••	••
Tensile strength	••	•••	•••	•	••	••
Permanent deformation	••	•	••	••	•••	••
Hydraulic oil, mineral	•••	•••	•••	–	•••	–
Hydraulic oil, synthetic ester	•	–	–	–	•	–
Non-polar solvents (e.g. petroleum spirit)	•••	••	••	–	•••	–
Polar solvents (e.g. acetone)	–	–	–	–	–	–
Ethyl alcohol	•••	–	–	•••	•	–
Isopropanol	••	–	–	•••	•••	–
Water	•••	–	–	••	••	–
Acids (10%)	–	–	–	•	•••	–
Alkaline solutions (10%)	••	•	•	•••	••	–

••• Highly suitable •• very suitable • suitable – unsuitable ® Vulkollan® is a registered trademark of Bayer

Table 3. Suction cup material according to operating conditions (8)

Having gone through the five steps, introducing a couple of examples where the steps are applied would be useful for a better understanding on how to use the five steps. The first example carries the following given:

- Weight of the workpiece: 0.3 $[Kg]$
- Material of the workpiece: Glass
- Shape of the workpiece: curved with no flat surface
- Suction cup orientation: Horizontal
- Direction of movement: Vertical
- Acceleration of the system: 35 $\left[\frac{m}{s^2}\right]$
- Environment: humid space due to boiling water for some nearby process

So, step 1 is already in the given which leads to step 2 that is the selection of the shape of the suction cup, it is given that the workpiece has a curved surface and is from glass so the optimal suction cup shape would be the Bellows suction cup with 3.5 convolutions due to the workpiece being from a delicate material (glass) and is curved. Now moving to step 3 that is the calculation of the retention and breakaway forces using *equation.11*:

$$F_H = m * (g + a) * S$$
$$F_H = 0.3 * (9.81 + 35) * 1.5$$
$$F_H = 20.1645\ N$$

The factor of safety used was 1.5 due to the movement being a translation motion. This leads to step 4 which is the suction cup dimensions (diameter in our case), referring to *table.2* in *page.21* it is shown that a bellows suction cup with 3.5 convolutions suction cup having a diameter of 30 mm is optimal.

Finally, step 5 which is deciding on the material of the suction cup. What is known is that the workpiece is from glass, it is next to a process which has boiling water involved so the temperature is relatively high but nothing exceeding 40 degrees Celsius, and that there will be water vapor in the air so that must be factored in by keeping in mind the interaction of the water particles. Given what is known one could see that selecting Nitrile rubber is the most optimal material for the suction cup due to it satisfying the operating temperature, works with glass, and has good resistance against water.

The second example to reinforce the understanding of how to go by the five steps will have the following given:

- Weight of the workpiece: 2 $[Kg]$
- Material of the workpiece: Wood
- Shape of the workpiece: Long plank
- Suction cup orientation: Vertical
- Direction of movement: Vertical
- Acceleration of the system: 10 $\left[\frac{m}{s^2}\right]$
- Environment: Dry atmosphere with decent wind

Similarly to what was done in the previous example, the start point will be from step 2 since step 1 is already in the given. It is known that the planks of wood are oblong so it would be best if an oval suction cup is used to handle it. Moving on to step 3, the retention and breakaway forces are calculated using the appropriate formula from *equation.13*:

$$F_H = \left(\frac{m}{\mu}\right) * (g + a) * S$$

$$F_H = \left(\frac{2}{0.5}\right) * (9.81 + 10) * 1.5$$

$$F_H = 118.86\ N$$

The factor of safety used was 1.5 due to the movement being a translation motion, and the friction coefficient is 0.5 because the workpiece is made from wood. Step 4 is next, which is determining the size of the suction cup to properly be able to secure the workpiece. Looking at *table.2* in *page.21* it is shown that the suction cup size $30 \times 90\ mm$ is sufficient according to the calculated retention forces.

Finally, step 5 is about picking the suction cup material according to the conditions. The environment has a dry atmosphere with some wind that must be considered, according to *table.3* in *page.22* we see that Vulkollan® is optimal for usage due to it being very suitable with wood, and with atmospheric conditions such as the ones given in this example.

1.6 FluidSIM®

To conclude the theoretical section of this document, the program that will be used for the practical part will be introduced in this subchapter. The program is called FluidSIM® from the company FESTO and it is a circuit diagram design and simulation program for pneumatics, hydraulics, and electrical engineering.

The main screen structure of the program with the final task simulation is displayed in *Figure.25:*

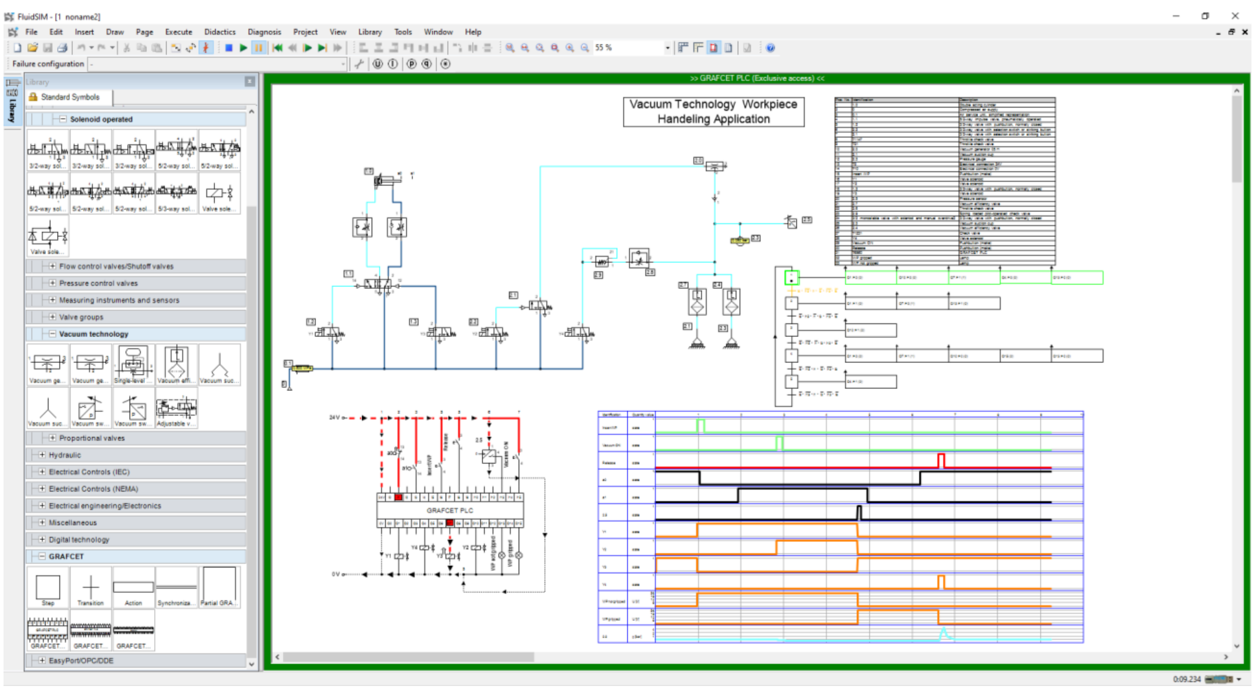


Figure 25. Main screen structure of FluidSIM®

Using this program, the electropneumatic circuits to control the incremental tasks of application of vacuum technology will be illustrated. Having established that, the doors to means of control other than electropneumatic circuits arise. The circuits following the electropneumatic circuits will be controlled by a virtual PLC that is programmed using GRAFCET language as it is considered the modern mean of control.

Chapter 2

2.1 Partial vacuum measurement

Now that we the foundation of the study has been established, one can start to look at how to create circuits that will develop the understanding of how vacuum technology works. The electropneumatic circuits in *subchapter 2.1* and *subchapter 2.2* will be the circuits from TP230 material in FluidSIM® program redone for the sake of understanding. With the circuit in *Figure.26* the measurement of the partial vacuum will be possible:

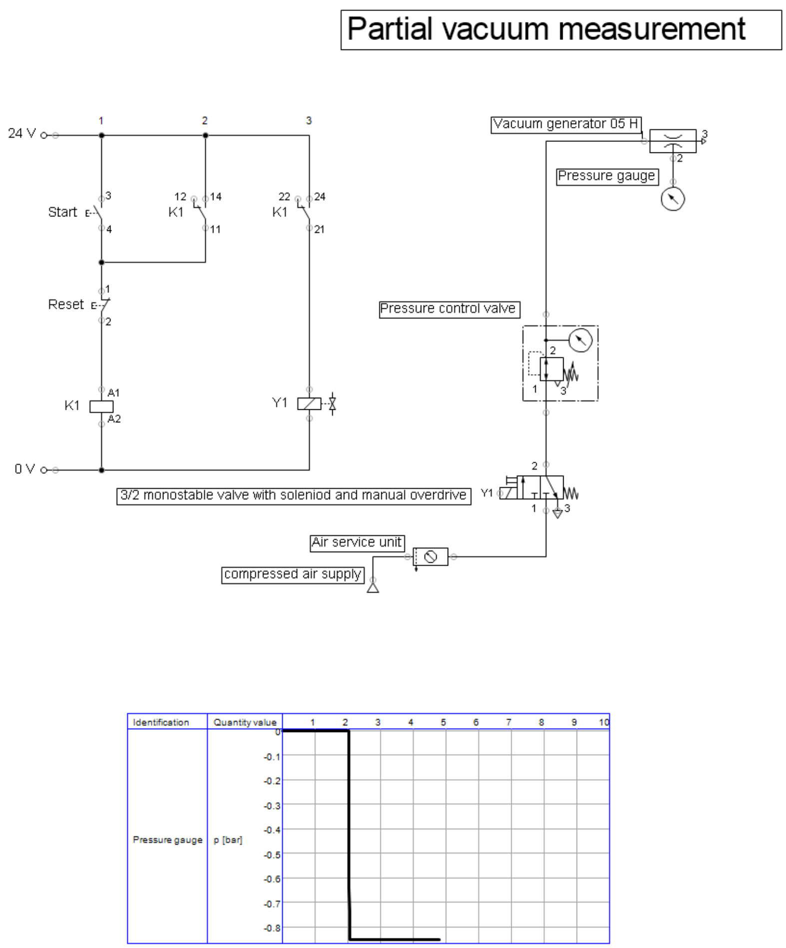


Figure 26. Partial vacuum measurement FluidSIM® electropneumatic circuit

It should be noted that since this is the first circuit, the parts that are involved will be defined for the understanding of the preceding tasks.

The components that were used are:

- Electrical power supply (24V connection & 0V connection)

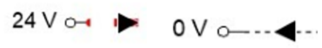


Figure 27. Electrical power supply (24V connection & 0V connection)

- Pushbutton (make)

Figure 28. Pushbutton (make)

- Pushbutton (break)

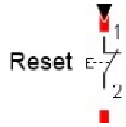


Figure 29. Pushbutton (break)

- Two changeover switches

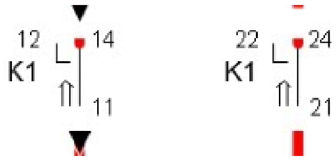


Figure 30. Two changeover switches

- Relay: Picks up when a certain percentage of the nominal voltage is applied and drops out again when the voltage falls below a certain percentage of the nominal voltage.

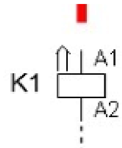


Figure 31. Relay

- Valve solenoid: The valve solenoid switches the valve. By means of a label the valve solenoid can be linked to a valve that is solenoid operated.

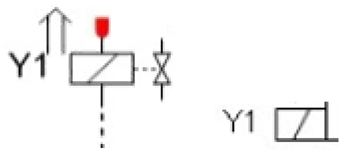


Figure 32. Valve solenoid

- Compressed air supply

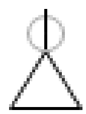


Figure 33. Compressed air supply

- Air service unit

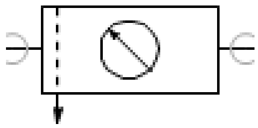


Figure 34. Air service unit

- 3/2 monostable valve with solenoid and manual override

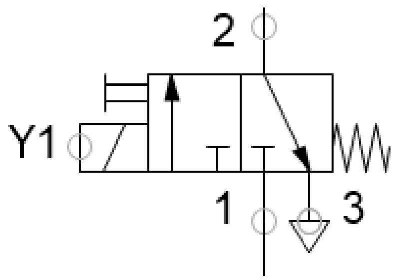


Figure 35. 3/2 monostable valve with solenoid and manual override

- Pressure control valve with manometer

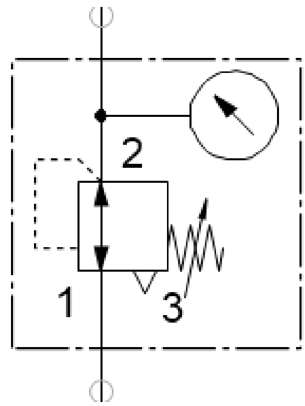


Figure 36. Pressure control valve with manometer

- Vacuum generator 05 H / 05 L

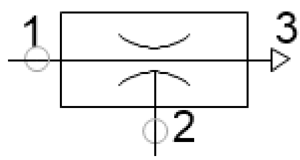


Figure 37. Vacuum generator 05 H / 05 L

- Pressure gauge

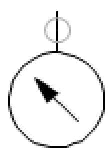


Figure 38. Pressure gauge

The correlation of which part is which have been set so that the components of the system are better understood and found.

In *Figure.26* the vacuum generator 05 H is used, however the same setup can be kept and the vacuum generator 05 H be replaced with vacuum generator 05 L. These two vacuum generators differ in the fact that the H type has a wider range for partial vacuum (up to -0.85 bar) while the L type is limited to up to -0.6 bar.

So, in this task we the partial vacuum generated is being measured with respect to the system pressure and recording those values.

The data of the measurement of partial vacuum will be displayed in *table.4*:

System Pressure	Partial vacuum [bar]	
	Vacuum generator 05 H	Vacuum generator 05 L
1 bar	-0.168	-0.099
2 bar	-0.337	-0.198
3 bar	-0.506	-0.297
4 bar	-0.660	-0.397
5 bar	-0.843	-0.496
6 bar	-0.850	-0.595

Table 4. Partial vacuum due to system pressure

The trend more clearly shows itself when the graph of the results from the *table.4* are plotted in *Figure.39*:

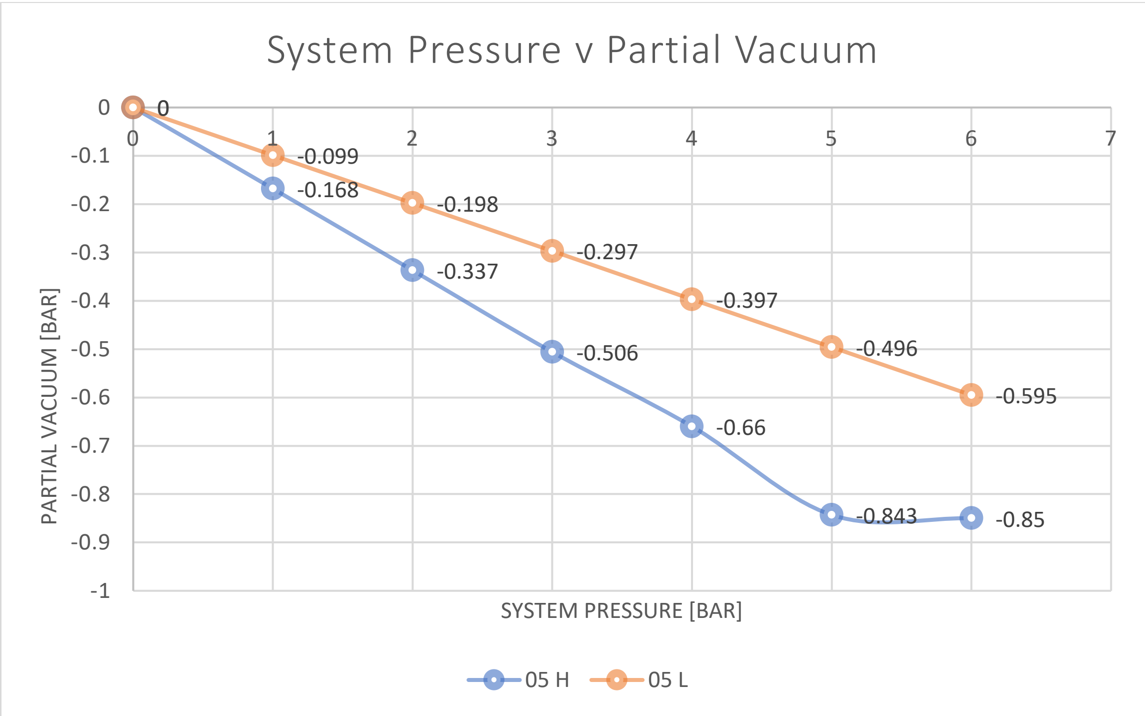


Figure 39. System Pressure v Partial Vacuum

The broader range of the H type vacuum generator can be seen more clearly in *Figure.39*. The operating pressure for the H type is up to 6 bar and that's when one could no longer get better partial vacuum pressure results if the system pressure is increased, and it can be clearly seen that the operating pressure for the L type is up to 5 bar since negligible insignificant change in partial vacuum pressure from the system pressure at 5 bar to 6 bar is noticed which only highlights more of the difference between both vacuum generator types.

2.2 Evacuation time Measurement

With the circuit in *Figure.40* one would be able to measure the evacuation time, however since this task has to be simplified in a sense, an air pressure reservoir will be used as a replacement for multiple suction cups for the sake of the measurement.

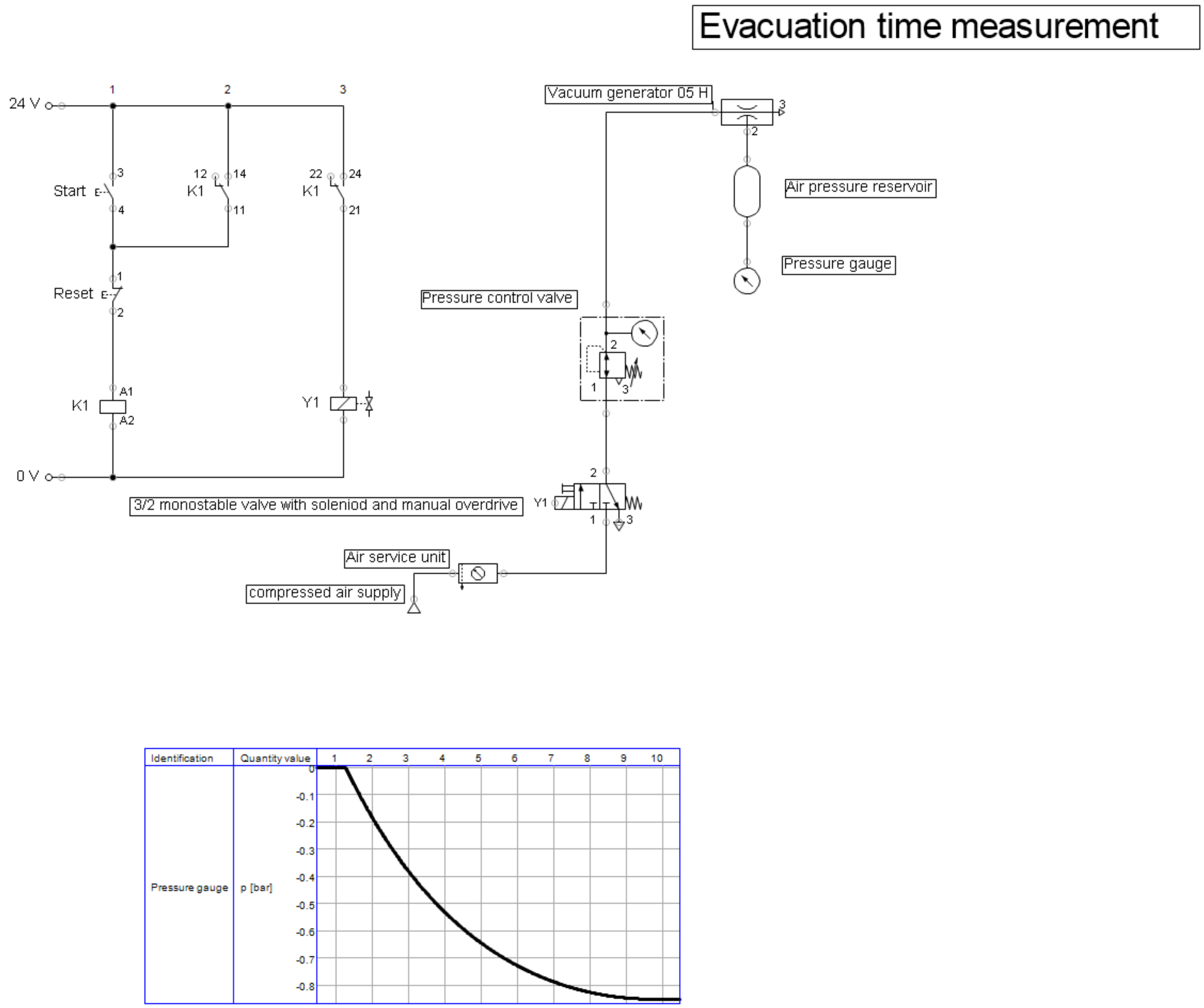


Figure 40. Evacuation time measurement FluidSIM® electropneumatic circuit

The components will be listed in the next page.

The components that were used are:

- Electrical power supply (24V connection & 0V connection)
- Pushbutton (make)
- Pushbutton (break)
- 2 changeover switches
- Relay
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- Air pressure reservoir (0.4 L)

So here the time it takes for us to achieve the proper partial vacuum for both types of the vacuum generators the H type and the L type will be monitored. This will give an insight into why using the L type is even considered if it gives a narrower spectrum of partial vacuum pressures with respect to the system pressure compared to the H type which offers a wider range.

These incremental tasks are good for understanding the reasoning behind what is happening and how to measure the important information one at a time till a place which we can measure all the important information in one control system is reached.

The data of the measurement of evacuation time will be displayed in *table.5*:

Partial vacuum [bar] (System Pressure set at 6 bar)	Evacuation time [secs]	
	Vacuum generator 05 H	Vacuum generator 05 L
-0.1 bar	0.2	-
-0.2 bar	0.6	0.3
-0.3 bar	1.2	0.5
-0.4 bar	1.7	0.8
-0.5 bar	2.4	1.1
-0.6 bar	3.2	2
-0.7 bar	4.3	-
-0.85 bar	10	-

Table 5. Evacuation time due to partial vacuum

The trend more clearly shows itself when the graph of the results from the *table.5* are plotted in *Figure.41*:

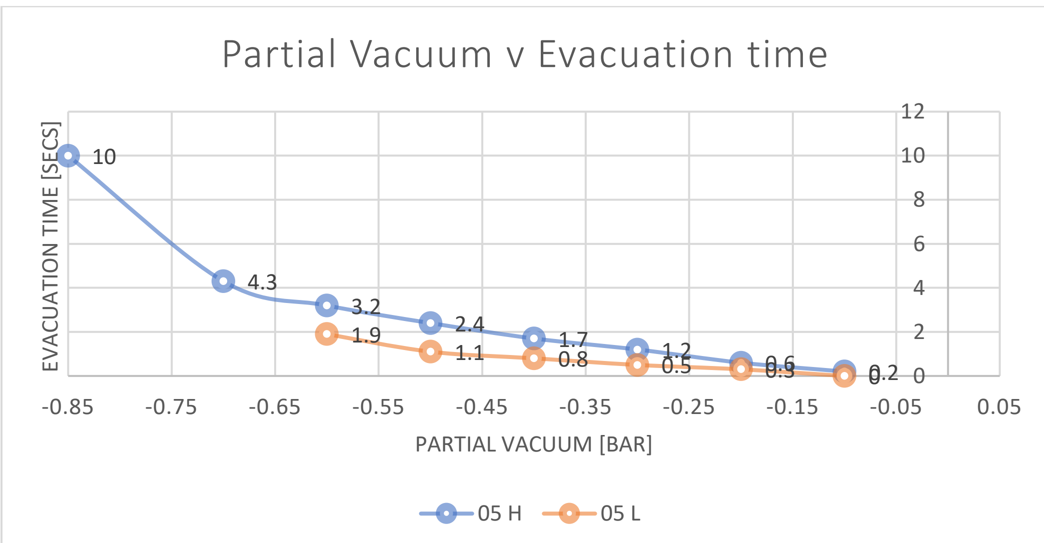


Figure 41. Partial Vacuum v Evacuation time

With this data measured one can conclude that the L type vacuum generator is more time efficient when it comes to lower partial vacuum pressures. The approximately 1 second difference might seem trivial but when it is considered in an industrial application where such a process has to be repeated many times it is realized that many resources are saved going for the L type rather than the H type. This also brings to light the awareness that must be had when making decisions of what vacuum generator to use because it would save lots of money and make the process most efficient.

These circuits are recreated from the material in the program FluidSIM® under “circuits for exercises TP 230 Vacuum technique” which are controlled by means of self-sustaining electropneumatic circuits, however my work is to program those tasks using a GRAFCET virtual PLC so in *subchapter 2.3* and *subchapter 2.4* both “Partial vacuum measurement” and “Evacuation time measurement” will be redone, however controlled by a GRAFCET virtual PLC rather than the electropneumatic circuits shown in the last two chapters.

2.3 Partial vacuum measurement (GRAFCET)

The task of how to measure partial vacuum pressure has been put forth in *subchapter 2.1*, however it was being controlled by an electropneumatic self-sustaining circuit while now the same measurement will be shown in *Figure.42* controlled using a GRAFCET virtual PLC:

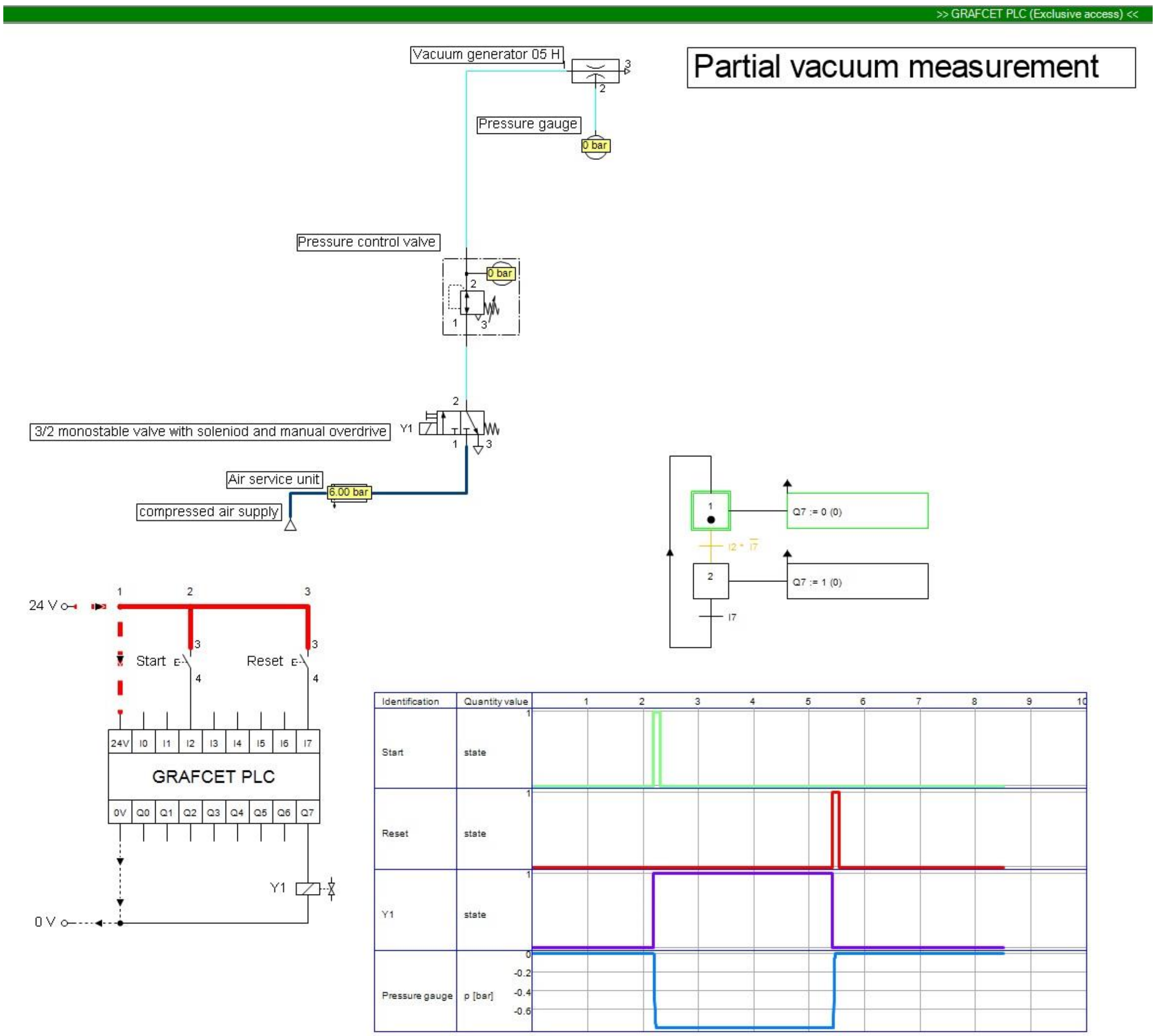


Figure 42. Partial vacuum measurement FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- 2 Pushbuttons (make)
- 2 changeover switches
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- GRAFCET Virtual PLC

Taking a look at the GRAFCET PLC one can see 8 ports + supply port on top and 8 ports + supply port in the bottom, the ports represent inputs and outputs where I0 to I7 are the inputs and Q0 to Q7 are the outputs.

List of virtual PLC inputs:

- Start push button
- Release push button

List of virtual PLC outputs:

- Y1 solenoid

Moving to the GRAFCET program squared boxes are seen; these boxes represent steps. The box with the double border is what is referred to as an initial step that determines the initial state of the system. The cross-junction shape below each step is a transition where the conditions are defined and have to be met to be able to move to the next step. And finally, the rectangles to the right of the steps represent actions that are desired as a consequence of having met the conditions from the transition before. The actions can be simple actions where if they were triggered by the step, they send a signal to the appropriate output till the next step is activated where that signal goes back to logical value 0. In these tasks, actions with memory or "action on activation" will be used to keep the self-sustaining circuit such as the electropneumatic circuit of this measurement in *subchapter 2.1*. One must take a look at the GRAFCET program in *Figure.43* to understand more about the process that the PLC goes through:

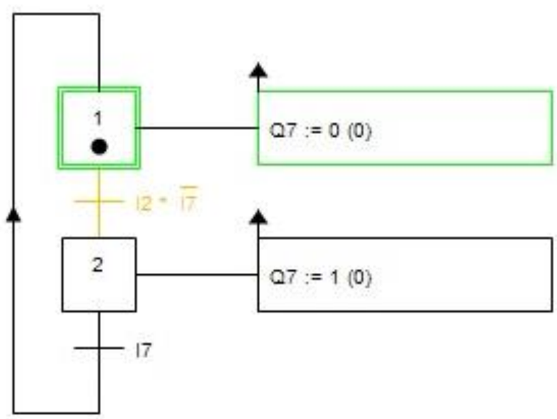


Figure 43. Partial vacuum measurement (GRAFCET) GRAFCET program

It must be understood how the system is working with this program to operate and proceed to further steps. The initial step sets the output Q7 which is linked to Y1 to logical value 0 with memory, meaning that the signal of the output Q7 will remain logical value 0 until it is decided otherwise. Now transition condition is a very important step that needs to be understood. There are two push buttons assigned to inputs I2 and I7 (Start and Release respectively) that means that there are four different combinations of those inputs coming from the *equation.14* that states how many different combinations can one have with n number of variables (inputs):

$$Different\ combinations\ of\ n\ number\ of\ inputs = 2^n$$

Equation 14. Different combinations of n number of inputs

Given that there are four different combinations a transition must be attached to the desired combination, which in this case is pushing the start button without pushing the release button. The system will wait for that specific combination to move to the next step so if both push buttons were to be pressed at the same time or no button is pressed or the release button is pressed the system will not proceed to the next step to execute the next action. Moving on to the next step where the action set is to change the signal of the output Q7 to logical value 1 and have it remain that way till it is ordered otherwise using a transition condition and another step with the action to set it back to logical value 0 and hold. The last transition condition contains only one input because it is saying that out of the four combinations of the two inputs, it is desired to execute the transition when the input signal I7 has logical value 1, meaning that if the release button is to be pushed alone or together at the same time with the start button execute the transition and go back to the initial step. The interaction of the signals and how the system behaves can be examined through the state diagram in *figure.44*:

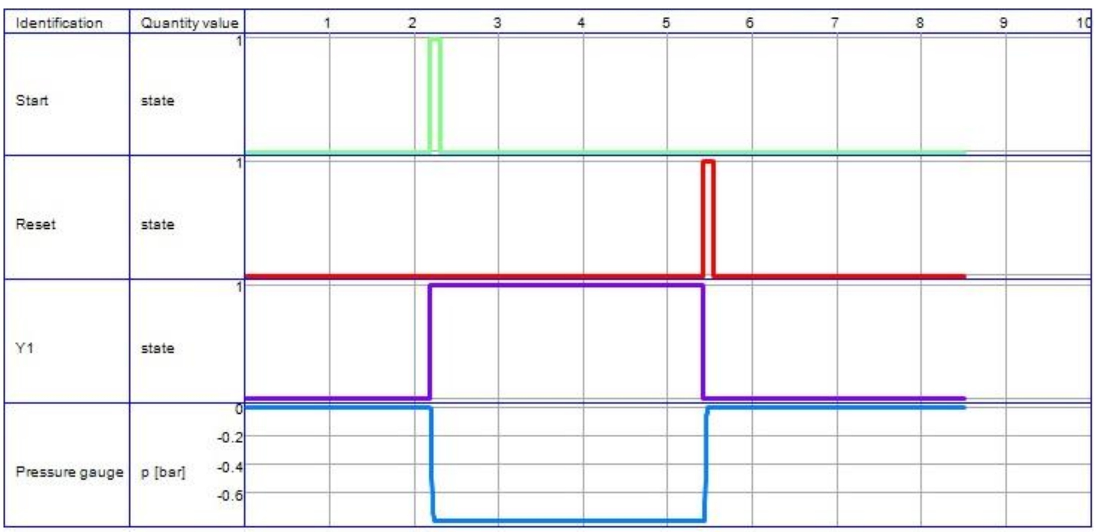


Figure 44. Partial vacuum measurement (GRAFCET) state diagram

Using this state diagram helps to see the work cycle and the signals responsible for initiating the vacuum generation and the signals responsible for stopping it.

Such a state diagram will be seen across all coming tasks so it is worthwhile to look at a more or less simple one and understand it to be able to move into more complex ones that will be there towards the last couple of tasks.

2.4 Evacuation time Measurement (GRAFCET)

Similarly, to what was done in the last measurement the GRAFCET virtual PLC will be used to control the evacuation time measurement that was introduced in *subchapter 2.2*:

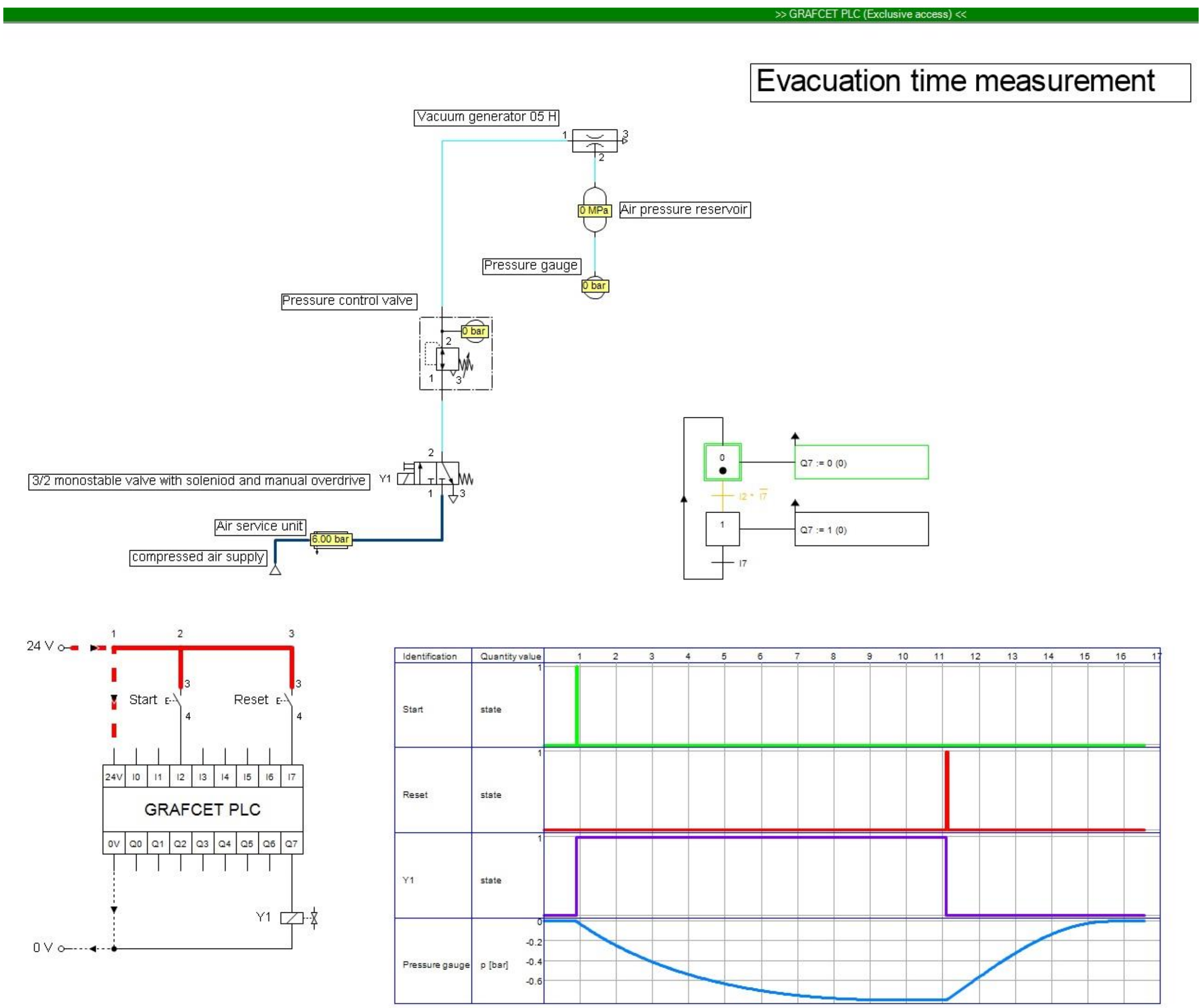


Figure 45. Evacuation time measurement FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- 2 Pushbuttons (make)
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- Air pressure reservoir (0.4 L)
- GRAFCET Virtual PLC

List of virtual PLC inputs:

- Start push button
- Release push button

List of virtual PLC outputs:

- Y1 solenoid

The study of the state diagram of this measurement will be in the next page to see the interaction between the signals.

The state diagram for this measurement is displayed in *Figure.46*:

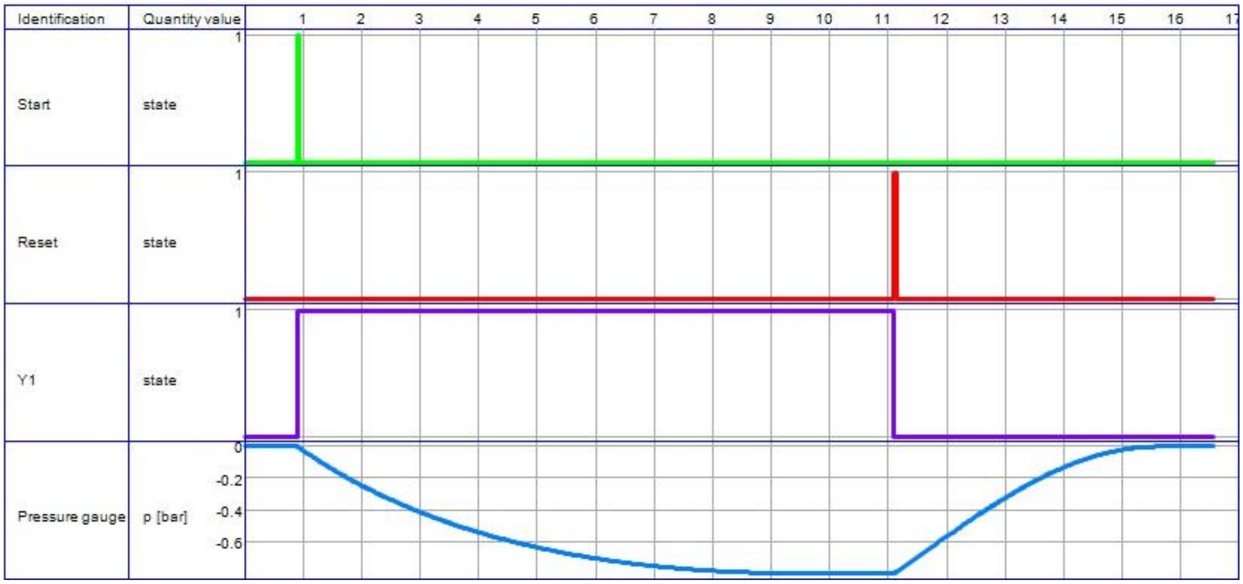


Figure 46. Evacuation time measurement (GRAFCET) state diagram

The initiating signal of the measurement is the start push button signal which activates the output signal Y1 that alters the 3/2 monostable valve to feed the vacuum generator compressed air to start generating the vacuum. It can be seen that the impact of the air pressure reservoir acting as multiple suction cups effects the pressure gauge reading on the state diagram in comparison to the partial vacuum measurement state diagram *Figure.44* where the reading was more or less a straight vertical line. The signal that sets the system back to its initial condition is the release push button signal by setting back the signal Y1 back to 0 causing the 3/2 monostable valve to cut the supply of compressed air to the vacuum generator.

The next tasks will aim at getting closer to being able to set up a fully functioning circuit for inserting workpieces and handling them through vacuum technology.

2.5 Maintaining vacuum when using more than one cup (GRAFCET)

In this task the ability to hold and maintain vacuum when using multiple suction cups is shown by using vacuum security valves/vacuum efficiency valves to prevent failure of the system if any suction cups fail for whatever reason:

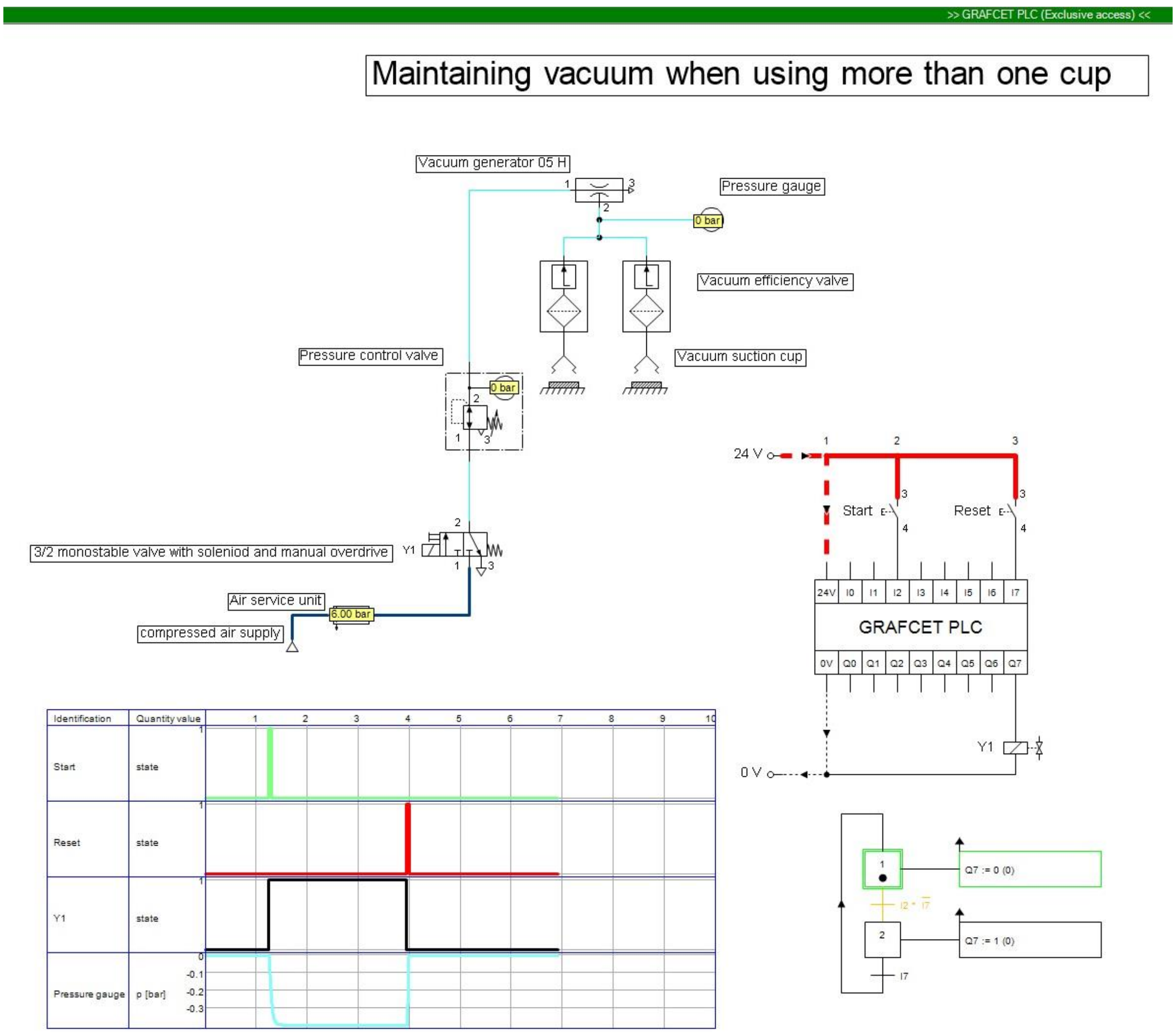


Figure 47. Maintaining vacuum when using multiple cups FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- 2 Pushbuttons (make)
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- GRAFCET Virtual PLC

List of virtual PLC inputs:

- Start push button
- Release push button

List of virtual PLC outputs:

- Y1 solenoid

It should be noted that the state diagram is practically the same as the partial vacuum measurement task's state diagram *Figure.44*, that is because it is fundamentally the same measurement however the goal here is to realize how the system works regardless of any sort of failure or disconnect from either suction cup.

The next page will contain the data tables when using the vacuum efficiency valves compared to not using them, and the combination of suction cups gripping the workpiece.

Data Tables:

No suction cups gripping the workpiece:

Vacuum generator	Partial vacuum without vacuum efficiency valve	Partial vacuum with vacuum efficiency valve
05 H	-0.004 bar	-0.413 bar
05 L	-0.011 bar	-0.541 bar

Table 6. Vacuum efficiency valve partial vacuum when no suction cups are gripping the workpiece

One suction cup gripping the workpiece:

Vacuum generator	Partial vacuum without vacuum efficiency valve	Partial vacuum with vacuum efficiency valve
05 H	-0.009 bar	-0.67 bar
05 L	-0.021 bar	-0.581 bar

Table 7. Vacuum efficiency valve partial vacuum when one suction cup are gripping the workpiece

Both suction cups gripping the workpiece:

Vacuum generator	Partial vacuum without vacuum efficiency valve	Partial vacuum with vacuum efficiency valve
05 H	-0.85 bar	-0.85 bar
05 L	-0.595 bar	-0.595 bar

Table 8. Vacuum efficiency valve partial vacuum when both suction cups are gripping the workpiece

It can be seen through this measurement that when vacuum efficiency valves are not used, the partial vacuum when there are no suction cups or one suction cup gripping the workpiece is practically 0 bar however when vacuum efficiency valves are used, suction would still be active.

2.6 Partial vacuum monitoring (GRAFCET)

In this task the intention is to monitor the partial vacuum pressure and the desired predetermined pressure is achieved a signal must be delivered to the worker operating the system to know that the right amount of partial vacuum has been achieved to proceed to the next step of the process.

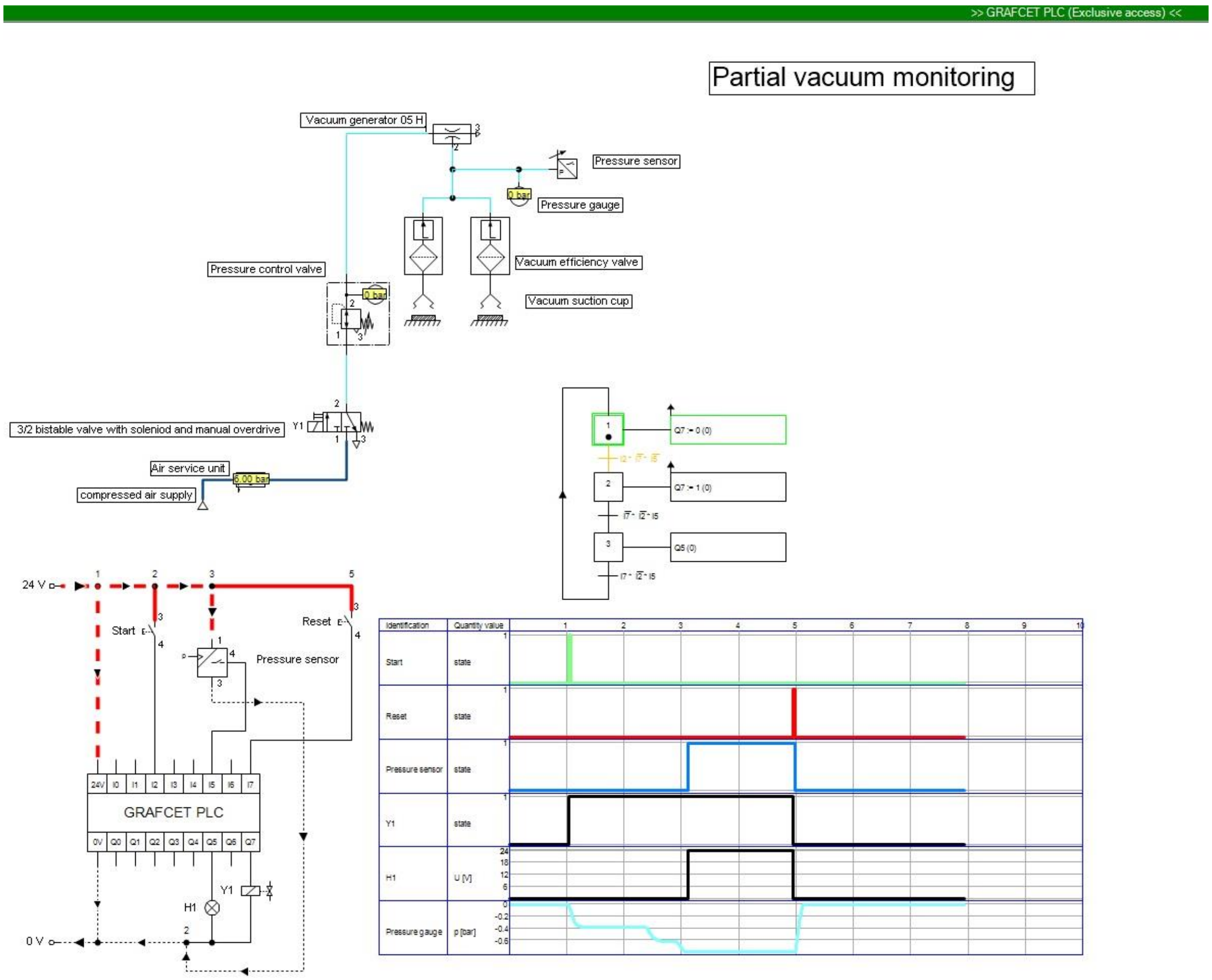


Figure 48. Partial vacuum monitoring FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- 2 Pushbuttons (make)
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor
- GRAFCET Virtual PLC

List of virtual PLC inputs:

- Start push button
- Release push button
- Pressure sensor

List of virtual PLC outputs:

- Y1 solenoid
- H1 lamp

The state diagram for this task is displayed in *Figure.49*:

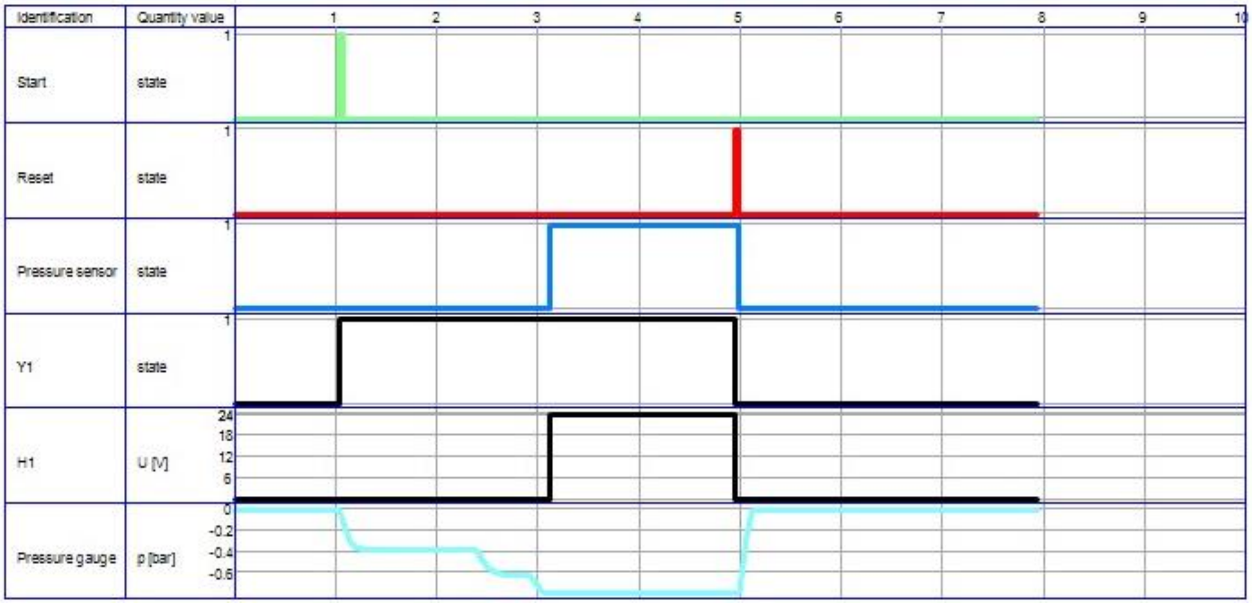


Figure 49. Partial vacuum monitoring (GRAFCET) state diagram

This state diagram shows that as the workpiece is gripped with the suction cup , the partial vacuum goes lower as it is seen in the last row of the state diagram, however it would not be enough and so the pressure sensor does not send the signal of logical value 1 to the input I5, however when the second suction cup is attached to the workpiece the predetermined partial vacuum pressure is reached and it activates the pressure sensor which then displays to the worker the lit lamp indicating that the workpiece is secured by the suction cups.

It can be seen through this measurement that when the desired level of partial vacuum pressure has been reached, the pneumatic pressure sensor activates a light to indicate to the worker that it is safe to commence with lifting or carrying the workpiece. It is used to make sure that the worker is on track on achieving the desired partial vacuum pressure.

2.7 Reducing compressed air consumption (GRAFCET)

In this task the objective is to minimize the amount of compressed air being consumed when using the tasks that have been done till now:

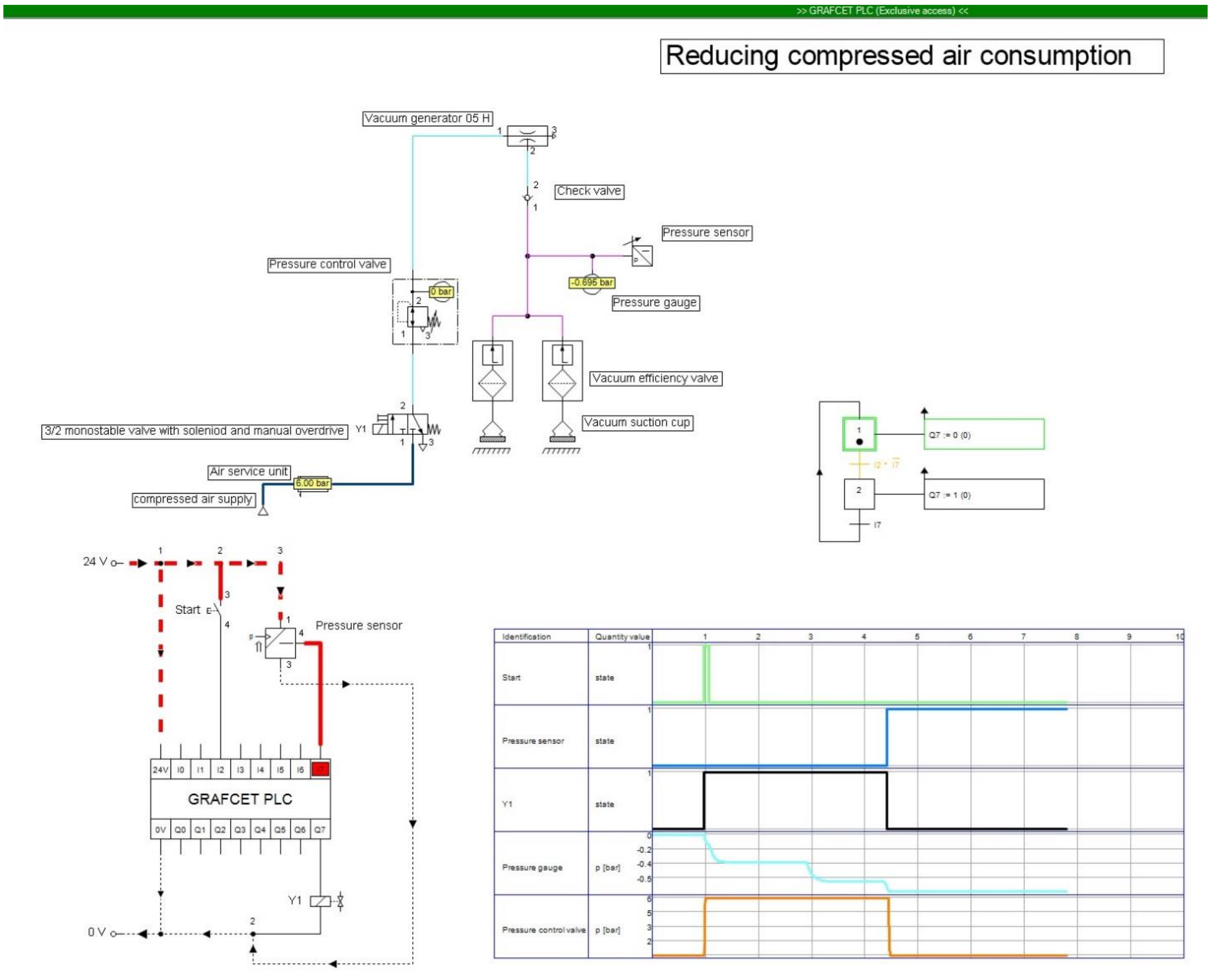


Figure 50. Reducing compressed air consumption FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- Pushbutton (make)
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor
- Check valve
- GRAFCET Virtual PLC

List of virtual PLC inputs:

- Start push button
- Pressure sensor

List of virtual PLC outputs:

- Y1 solenoid

The state diagram for this task is displayed in *Figure.51*:

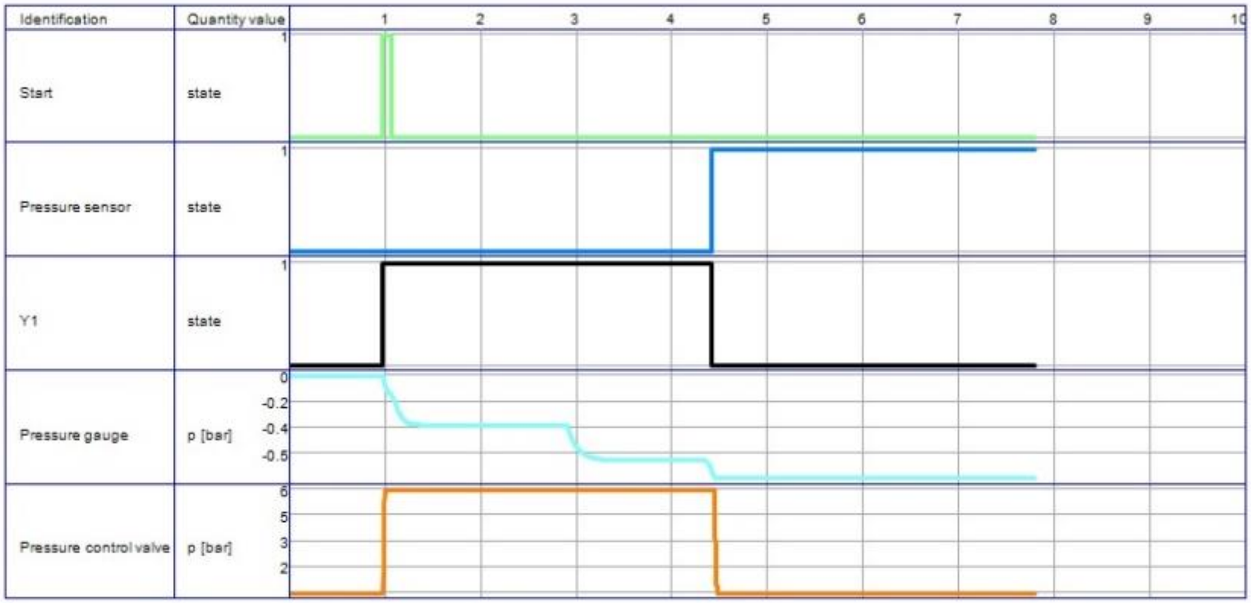


Figure 51. Reducing compressed air consumption (GRAFCET) state diagram

As always, the state diagram is always useful in seeing how the system is operated. Similarly to previous tasks the initiation is through the start push button signal stimulating the output Q7 which is connected to the output signal of the solenoid Y1 to start supplying compressed air to the vacuum generator as it is seen by the first drop in pressure in the fourth row, however that partial vacuum pressure is not sufficient and does not indicate that the suction cups have sufficiently gripped onto the workpiece, so when the suction cups sufficiently grip onto the workpiece (the next two drops in the partial vacuum pressure are due to the suction cups gripping one at a time), the desired partial vacuum pressure is finally achieved which triggers the pressure sensor input signal I7 to set the output signal Q7 to 0 causing the system to be cut off from compressed air as it can be seen in the last row which represents the supplied air pressure.

It can be seen through this task that the system will supply compressed air to the vacuum generator only when it’s really needed to do so, this saves a lot of resources over the course of time, and it is efficient and cost effective.

2.8 Controlled release of workpieces (GRAFCET)

The primary objective of this task is to have a controlled release of the workpiece according to set requirements:

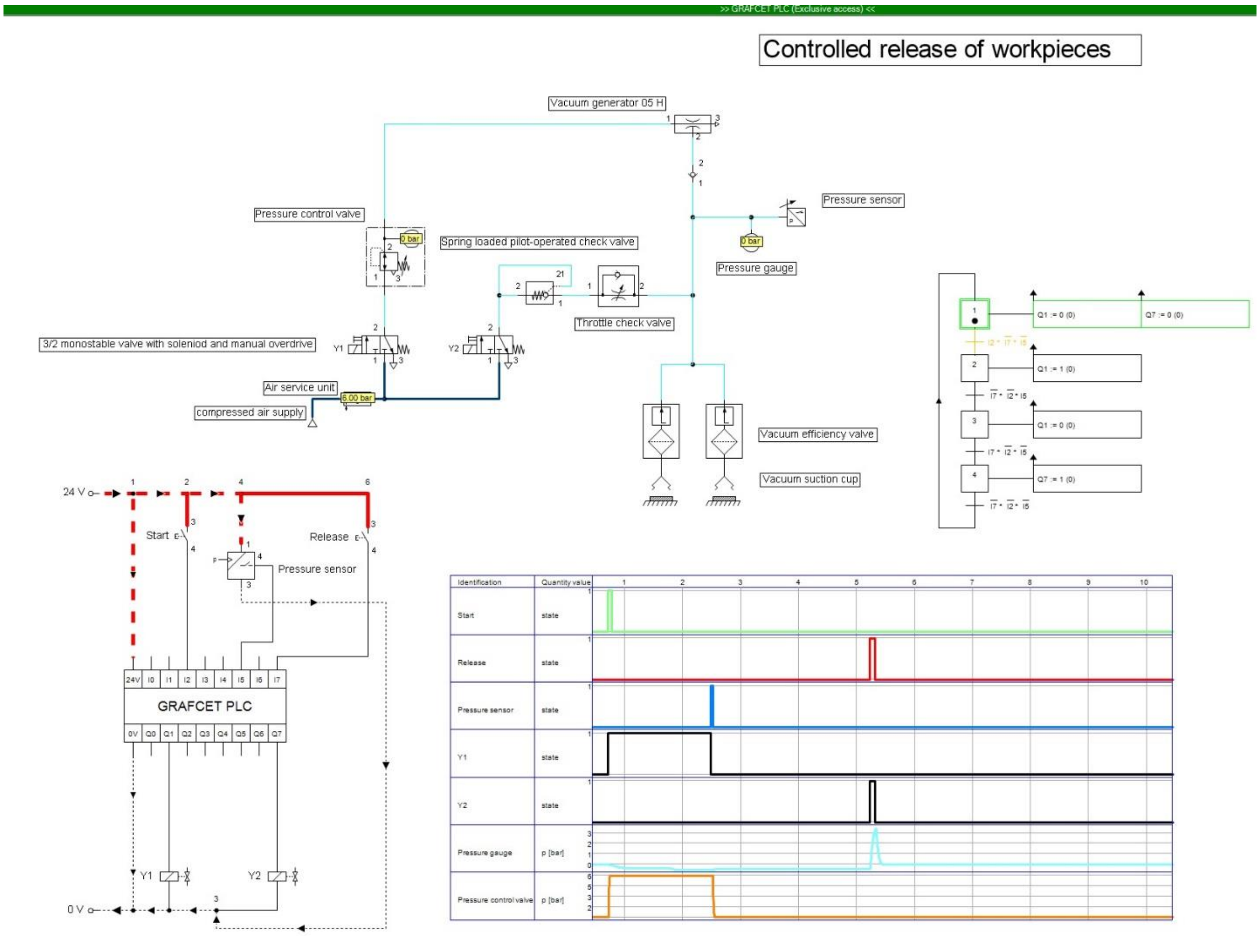


Figure 52. Controlled release of workpieces FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- 2 Pushbuttons (make)
- 2 Valve solenoids
- Compressed air supply
- Air service unit
- 2 3/2 monostable valves with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor
- Check valve
- Flow control valve
- Spring loaded check valve (piloted)

List of virtual PLC inputs:

- Start push button
- Pressure sensor
- Release push button

List of virtual PLC outputs:

- Y1 solenoid
- Y2 solenoid

The state diagram for this task is displayed in *Figure.53*:

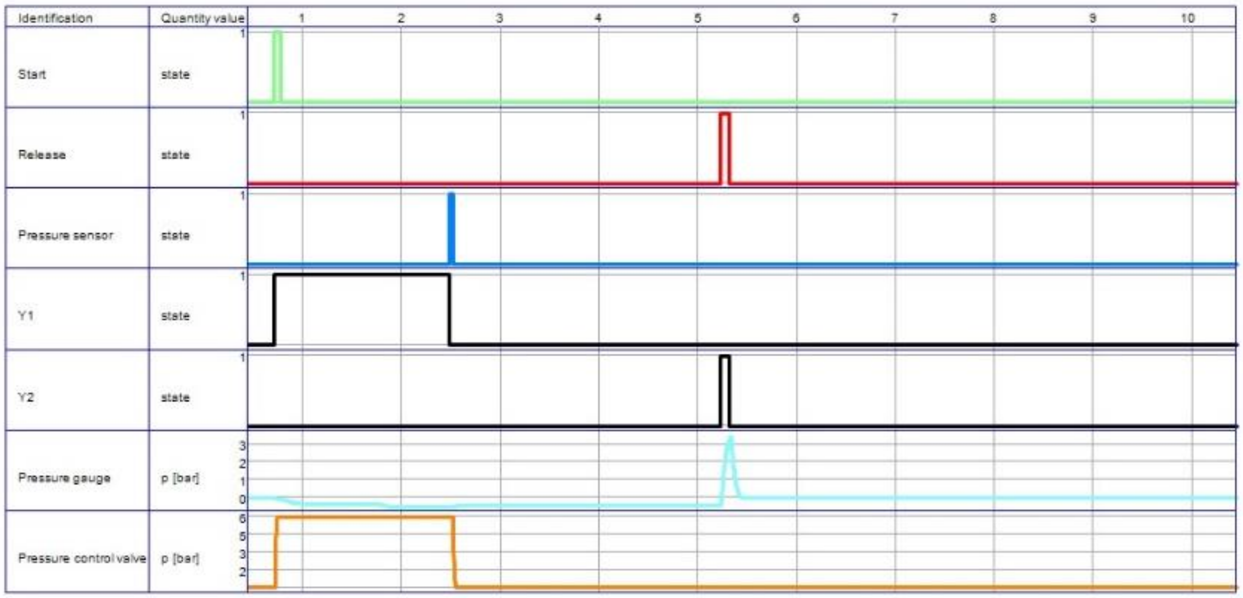


Figure 53. Controlled release of workpieces (GRAFCET) state diagram

The start signal causes the output signal Q1 to activate supplying compressed air into the vacuum generator, then the moment that the workpiece is gripped with both suction cups reaching the predetermined pressure, the signal of the pressure sensor is activated. Immediately after that the compressed air supply is cut off from the vacuum generator because the vacuum is maintained without it similarly to what was illustrated in *subchapter 2.7*. However, in this task it is shown how to control the release of the workpiece after having done manipulating it. The release signal causes output signal Q7 to activate which causes the opening of a pathway to the ambient air's pressure momentarily which can be seen as the spike in the row of pressure gauge.

The flow control valve can be adjusted to match the desired pace of release depending on the workpiece, conditions, and applications.

2.9 Basic Vacuum Technology Workpiece Handling Application (GRAFCET)

Now that the knowledge of how vacuum technology works and programming a few GRAFCET virtual PLCs have been gained, one can move to making a program of how the workpiece is fed and manipulated:

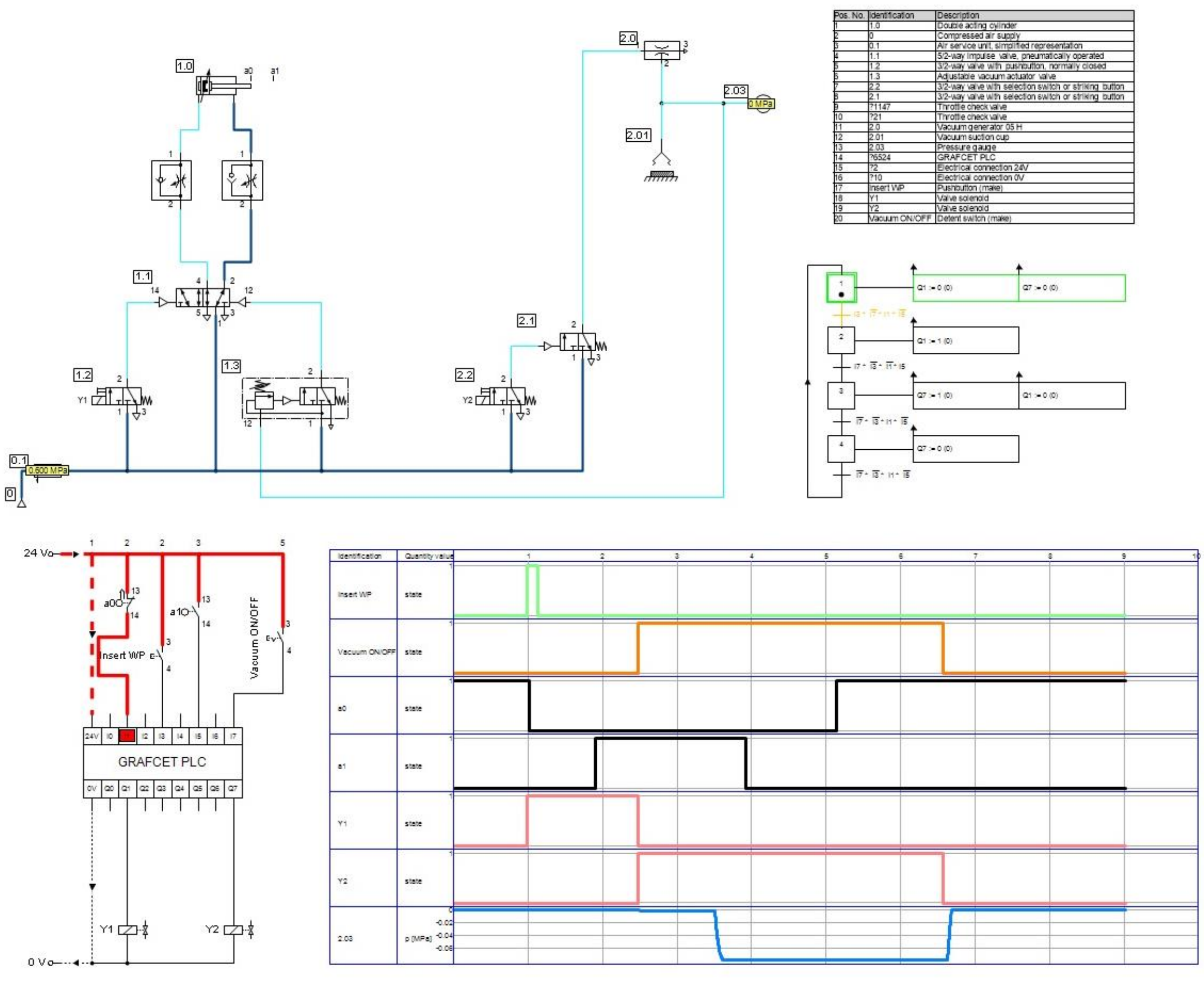


Figure 54. Basic workpiece handling application FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

Pos. No.	Identification	Description
1	1.0	Double acting cylinder
2	0	Compressed air supply
3	0.1	Air service unit, simplified representation
4	1.1	5/2-way impulse valve, pneumatically operated
5	1.2	3/2-way valve with pushbutton, normally closed
6	1.3	Adjustable vacuum actuator valve
7	2.2	3/2-way valve with selection switch or striking button
8	2.1	3/2-way valve with selection switch or striking button
9	?1147	Throttle check valve
10	?21	Throttle check valve
11	2.0	Vacuum generator 05 H
12	2.01	Vacuum suction cup
13	2.03	Pressure gauge
14	?6524	GRAFCET PLC
15	?2	Electrical connection 24V
16	?10	Electrical connection 0V
17	Insert WP	Pushbutton (make)
18	Y1	Valve solenoid
19	Y2	Valve solenoid
20	Vacuum ON/OFF	Detent switch (make)

Table 9. Basic workpiece handling application (GRAFCET) parts list

List of virtual PLC inputs:

- Insert WP push button
- Vacuum ON/OFF detent switch
- a0 make switch with roll
- a1 make switch with roll

List of virtual PLC outputs:

- Y1 solenoid
- Y2 solenoid

The state diagram for this task is displayed in *Figure.55*:

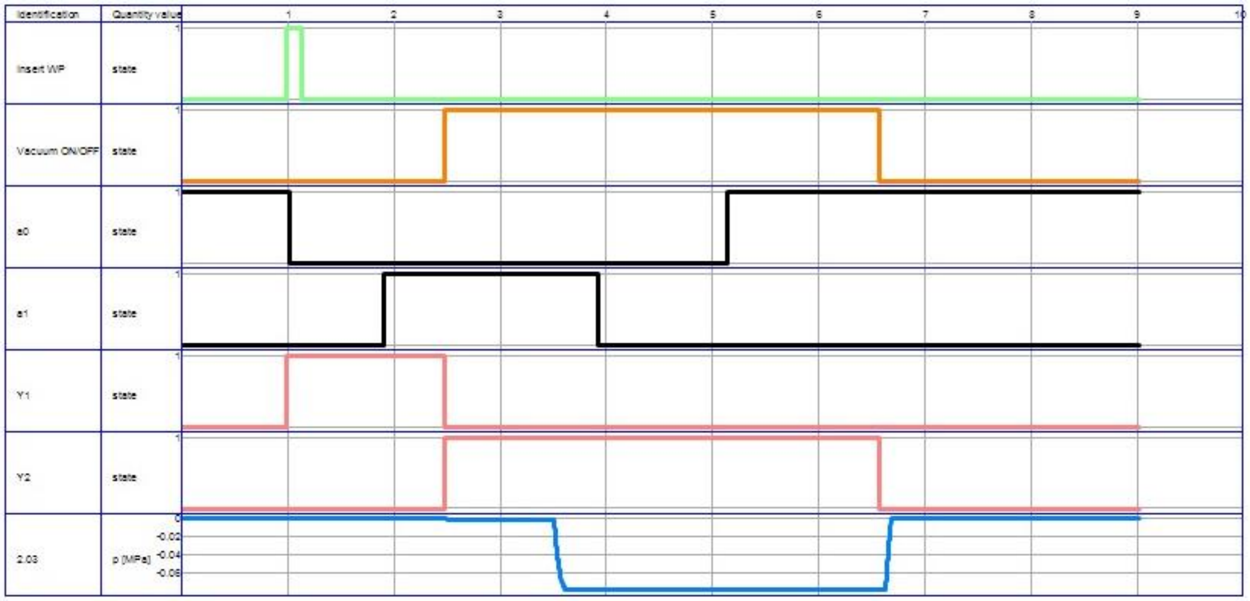


Figure 55. Basic workpiece handling application (GRAFCET) state diagram

This task is useful to see the interaction between the double acting pneumatic motor, the workpiece, and the suction cup. This layout can be thought of as workers put the workpiece on a stage that is controlled by the double acting pneumatic motor then the motor inserts it to the range of the suction cup and once the suction cup secures a grip on the workpiece the stage falls back for the workers to put the next workpiece to be handled. This task is generally the underlining basic idea behind a handful of vacuum technology applications in handling workpieces so it must really be understood to carry on the next task which would be the final task that is attempting to get as close to real life applications of the vacuum technology in a lot of industries.

2.10 Vacuum Technology Workpiece Handling Application with controlled release and vacuum security valves (GRAFCET)

This task will be combining the knowledge from all previous tasks to make an articulate representation of how workpieces should be handled using vacuum technology and is my design of how I picture the system interacting within itself:

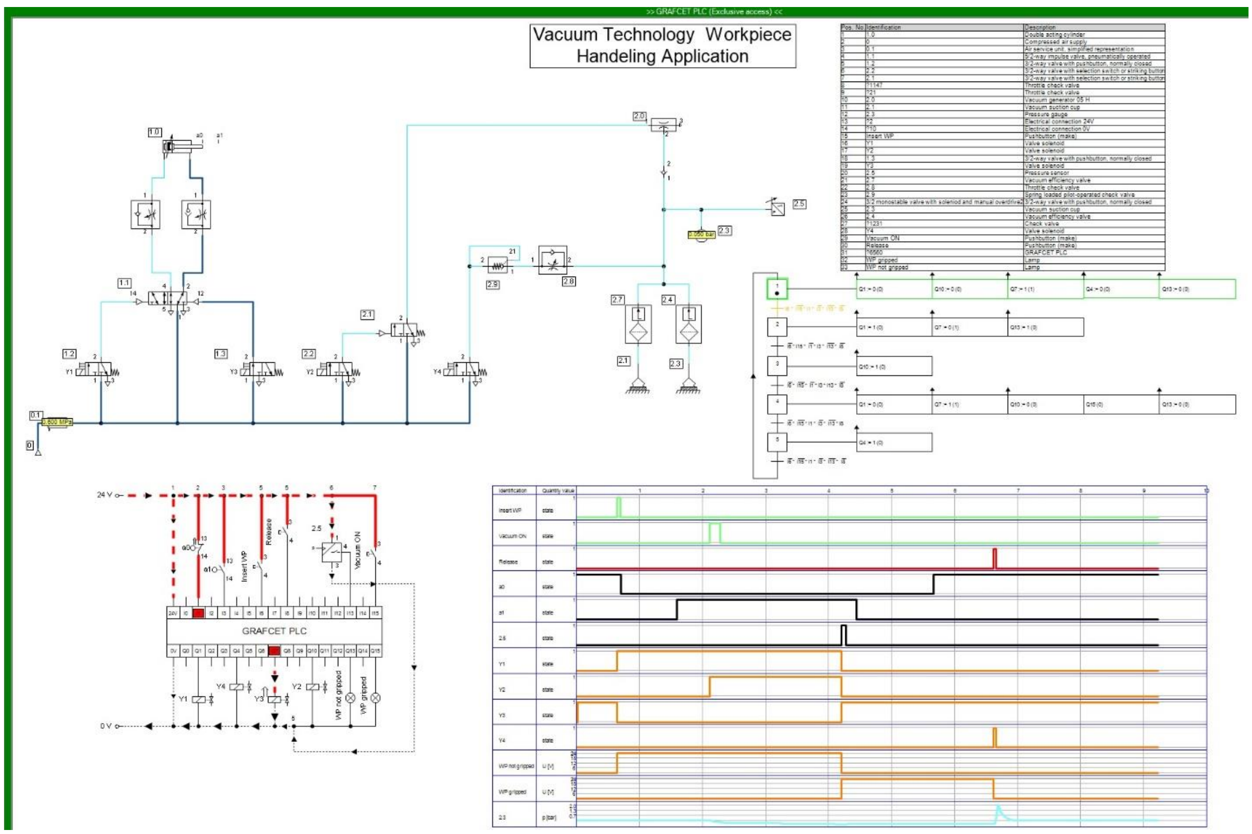


Figure 56. Advanced workpiece handling Application FluidSIM® circuit (GRAFCET)

The components, inputs and outputs will be listed in the next page.

The list of components used:

Pos. No.	Identification	Description
1	1.0	Double acting cylinder
2	0	Compressed air supply
3	0.1	Air service unit, simplified representation
4	1.1	5/2-way impulse valve, pneumatically operated
5	1.2	3/2-way valve with pushbutton, normally closed
6	2.2	3/2-way valve with selection switch or striking button
7	2.1	3/2-way valve with selection switch or striking button
8	?1147	Throttle check valve
9	?21	Throttle check valve
10	2.0	Vacuum generator 05 H
11	2.1	Vacuum suction cup
12	2.3	Pressure gauge
13	?2	Electrical connection 24V
14	?10	Electrical connection 0V
15	Insert WP	Pushbutton (make)
16	Y1	Valve solenoid
17	Y2	Valve solenoid
18	1.3	3/2-way valve with pushbutton, normally closed
19	Y3	Valve solenoid
20	2.5	Pressure sensor
21	2.7	Vacuum efficiency valve
22	2.8	Throttle check valve
23	2.9	Spring loaded pilot-operated check valve
24	3/2 monostable valve with soleniod and manual overdrive2	3/2-way valve with pushbutton, normally closed
25	2.3	Vacuum suction cup
26	2.4	Vacuum efficiency valve
27	?1231	Check valve
28	Y4	Valve solenoid
29	Vacuum ON	Pushbutton (make)
30	Release	Pushbutton (make)
31	?6560	GRAFCET PLC
32	WP gripped	Lamp
33	WP not gripped	Lamp

Table 10. Advanced workpiece handling Application (GRAFCET) parts list

List of virtual PLC inputs:

- Insert WP push button
- Vacuum ON push button
- Release push button
- Pressure sensor
- a0 make switch with roll
- a1 make switch with roll

List of virtual PLC outputs:

- Y1 solenoid
- Y2 solenoid
- Y3 solenoid
- Y4 solenoid
- WP not gripped lamp
- WP gripped lamp

The state diagram for this task is displayed in *Figure.57*:

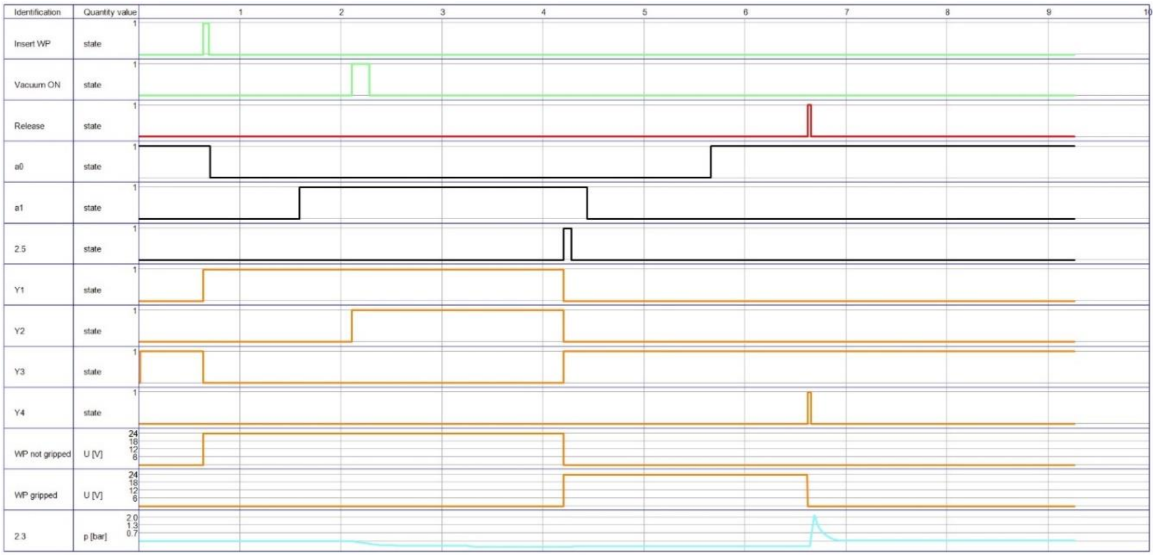


Figure 57. Advanced workpiece handling Application (GRAFCET) state diagram

The way this task works is by using the Insert WP signal to trigger the output signal Q1 which is connected to solenoid Y1 to cause the moving of the double acting pneumatic motor to the extracted position getting the workpiece in the range of the suction cup. After that, the signal from Vacuum ON triggers output signal Q10 which is connected to solenoid Y2 to supply compressed air to the vacuum generator to start the vacuum. However, the partial vacuum through the pressure sensor is not enough to trigger its signal so one must wait until the suction cups are gripping the workpiece and that is when the partial vacuum will be enough to trigger the pressure sensor which results in the WP gripped lamp to light up (which will be seen in *Figure.58* later), cutting off the compressed air flowing to the vacuum generator for the vacuum can held using the check valve to reduce compressed air consumption, and triggering output signal Q7 which is connected to solenoid Y3 to return the double acting pneumatic motor to its retracted position for loading of the next workpiece knowing full well that the first workpiece is secured by the suction cups. Finally, when one would want to release the workpiece the Release signal will trigger the output signal Q4 which is connected to solenoid Y4 to expose the system to the ambient pressure in a controlled manner through the flow control valve. This is a brief summary of how the system is meant to operate however complete conditions can be seen in the GRAFCET program in *Figure.59*.

Figure.58 captures a step in the process where the workpiece is secured, and the WP gripped green lamp lit up for the worker to know that the workpiece is secured by the suction cups:

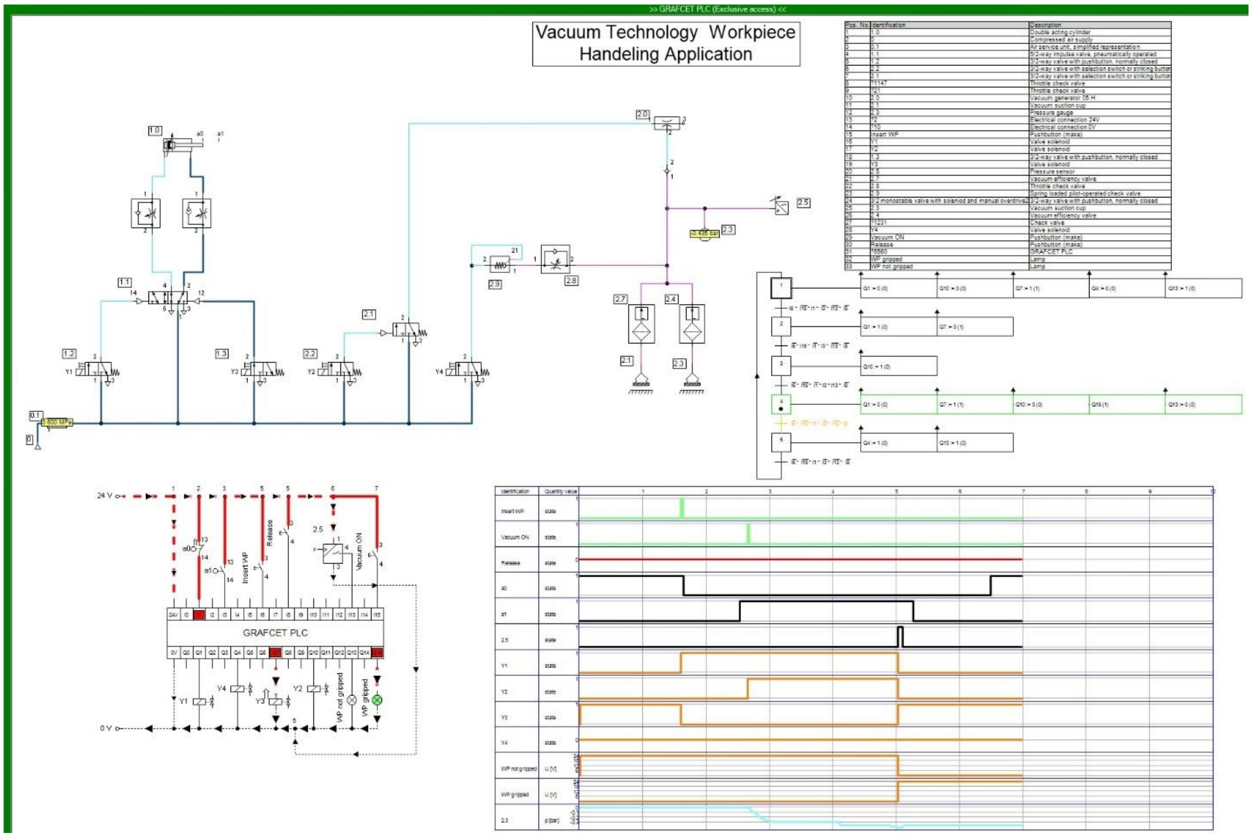


Figure 58. Advanced workpiece handling Application FluidSIM® (GRAFCET) WP gripped

The concepts within this task should be implemented in almost all applications dealing with handling workpieces for the sake of the efficiency of the work cycle and the resources used to carry out the task at hand.

The next page will be about the GRAFCET program of this task and highlighting the output signals according to its function and purpose.

The GRAFCET program of the task is displayed in *Figure.59*:

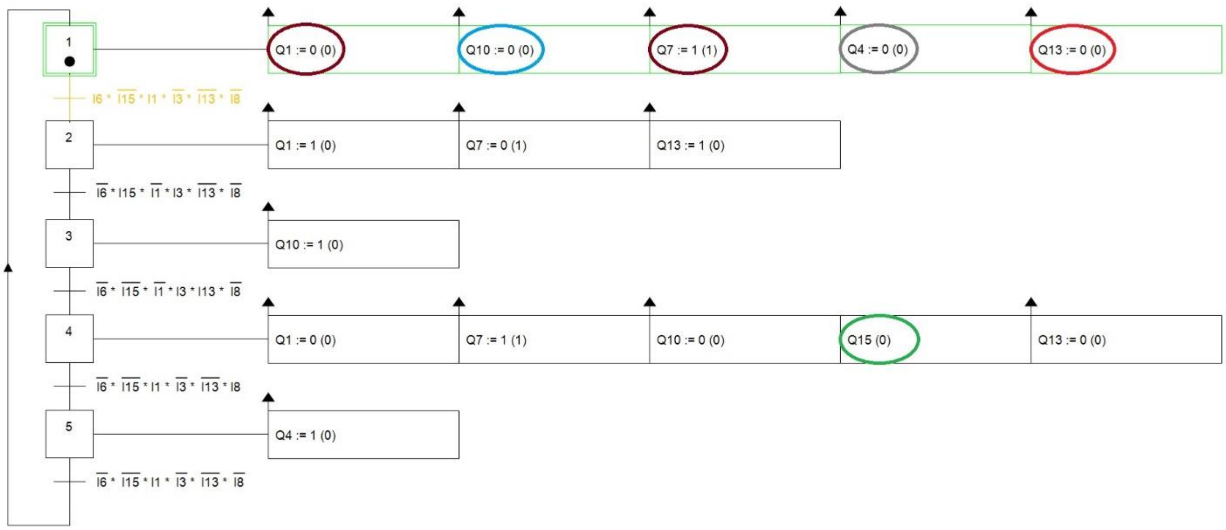


Figure 59. Advanced workpiece handling Application GRAFCET program with highlighted outputs

The labeled outputs suggest the following actions:

- Brown: position of the double acting pneumatic motor
- Blue: supply of compressed air to the vacuum generator
- Grey: release of the workpiece
- Red: indicating the workpiece isn't gripped
- Green: indicating the workpiece is gripped

The signal for WP gripped lamp is put as a simple action and not an action with memory because there is no need to do it with memory since it is only wanted on only for that particular step so it is sufficient to have it as a simple step while the WP not gripped signal has to remain on until the workpiece is secured with the suction cups and that is why action with memory is used.

Conclusion

I have studied the appropriate libraries (vacuum, electropneumatics and GRAFCET) which can be seen through all of *Chapter 2*, I have also studied material concerning vacuum technique TP230 from the didactic material in FluidSIM® and redone the electropneumatic circuits provided in that package which can be seen in *subchapter 2.1*, *subchapter 2.2* and the appendix. My main work revolves around programming and controlling the tasks at hand by a modern mean of control which is using a PLC. This period of time has been difficult and going to the university laboratories was not an option, so I had to program and simulate a virtual PLC using GRAFCET language which can be seen from *subchapter 2.3* to *subchapter 2.10.*

The tasks from *Chapter 2* illustrate the different functions that we must implement into a working system that is responsible for handling workpieces with vacuum technology, how it is important to monitor the pressure of the vacuum or the system, how to prevent the system from failing if one suction cup is not secured or fails, how to reduce the amount of resources invested still achieving the desired outcome, how to control the handling of the workpiece to not damage the suction cup or the workpiece, and finally how to consider interactions with other working parts in the system such as the double acting pneumatic motor seen in the last two tasks which is responsible for delivering the workpiece to the suction cup range.

This information builds up the very foundation of handling workpieces using vacuum technology and gives us the first couple of questions to ask ourselves when we are examining a system, or even trying to build a system. Having a solid basis of main functions that are needed in almost all applications with regards to handling workpieces using vacuum technology is a crucial position to be in.

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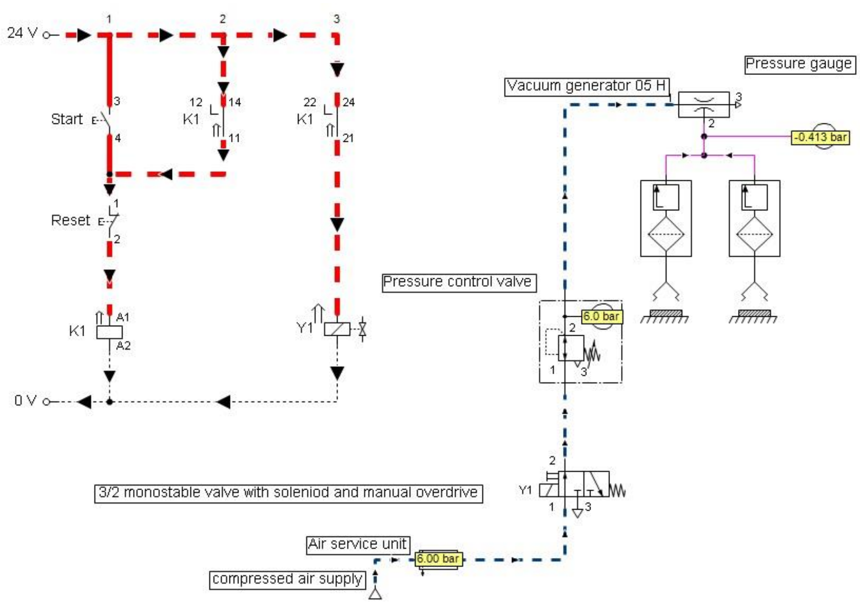
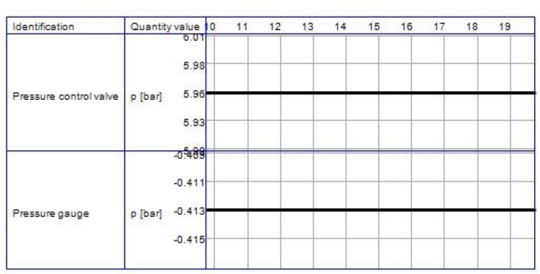
Appendix

1. Maintaining vacuum when using more than one cup

Using FluidSIM create a circuit for measuring the partial vacuum pressure when using more than one suction cups and how it changes when there is one cup gripping, none gripping, and both gripping. Then repeat the same measurement using vacuum efficiency valves this time to see how it can be a security mechanism to prevent from failure of other suction cups connected to the same vacuum generator to grip the workpiece.





The components will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- Pushbutton (make)
- Pushbutton (break)
- 2 changeover switches
- Relay
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups

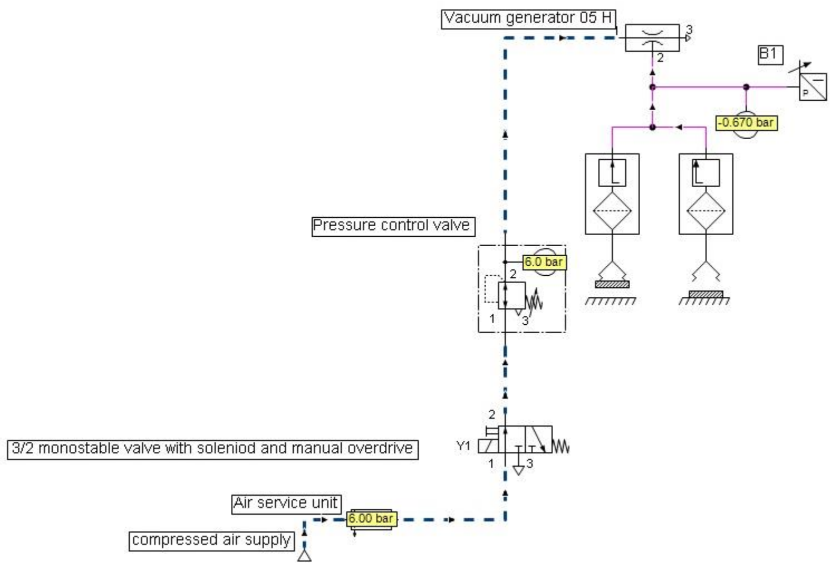
The data of the measurement is identical to the results found in *table.6*, *table.7* and *table.8* due to the measurement being exactly the same with the only difference being a different mean of control.

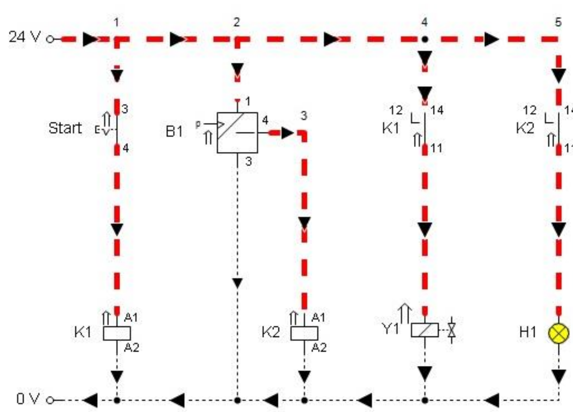
Conclusion:

It can be seen through this measurement that when using vacuum efficiency valves are not used, the partial vacuum when there are no cups or one cup gripping the workpiece is practically 0 bar however when vacuum efficiency valves are used suction is still active.

2. Partial vacuum monitoring

Using FluidSIM create a circuit for monitoring the level of partial vacuum pressure and give a response to the worker if the desired partial vacuum has been reached to lift or carry the workpiece.





The components will be listed in the next page.

The list of components used:

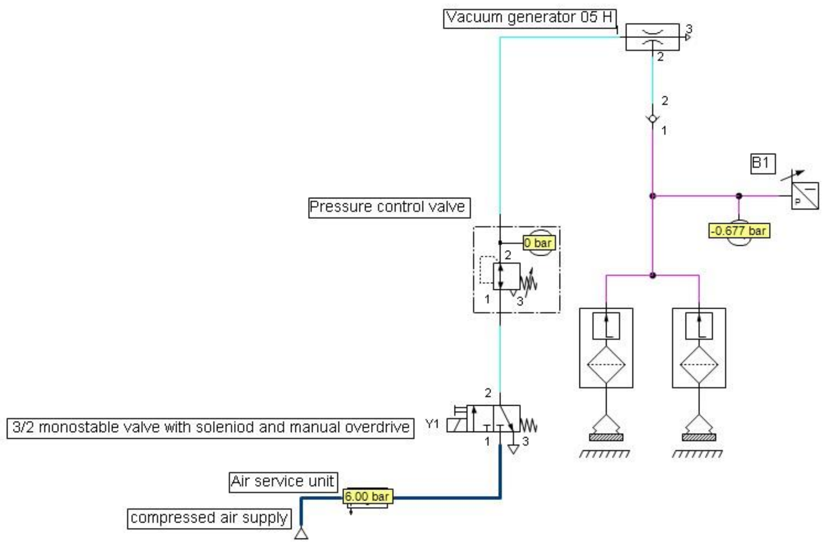
- Electrical power supply (24V connection & 0V connection)
- Pushbutton (with dent switch)
- 2 changeover switches
- 2 Relays
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor

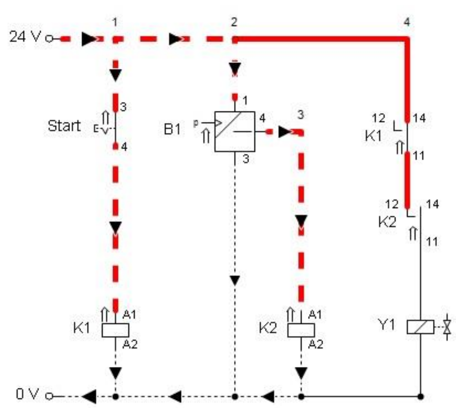
Conclusion:

It can be seen through this task that when the level of partial vacuum pressure that is desired is established, the pneumatic pressure sensor activates a light to indicate to the worker that it is safe to commence with lifting or carrying the workpiece. It is used to make sure that the desired partial vacuum pressure has been reached.

3. Reducing compressed air consumption

Using FluidSIM create a circuit for reducing the amount of compressed air used to achieve the desired partial vacuum pressure.





The components will be listed in the next page.

The list of components used:

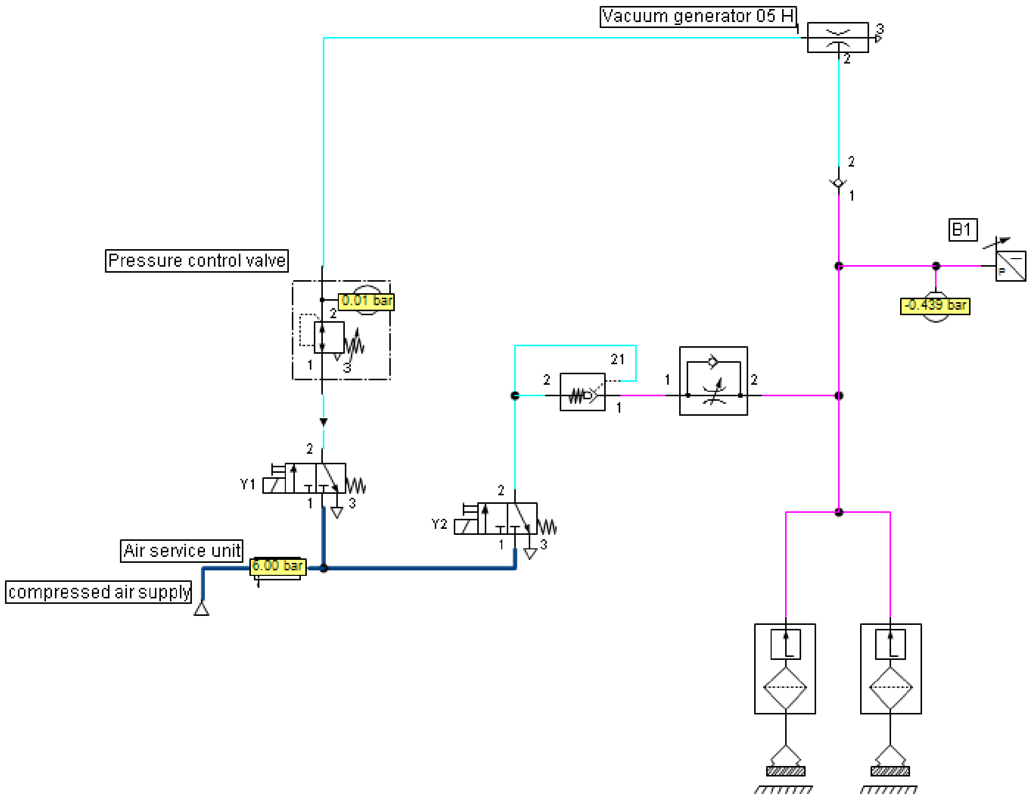
- Electrical power supply (24V connection & 0V connection)
- Pushbutton (with dent switch)
- 2 changeover switches
- 2 Relays
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor
- Check valve

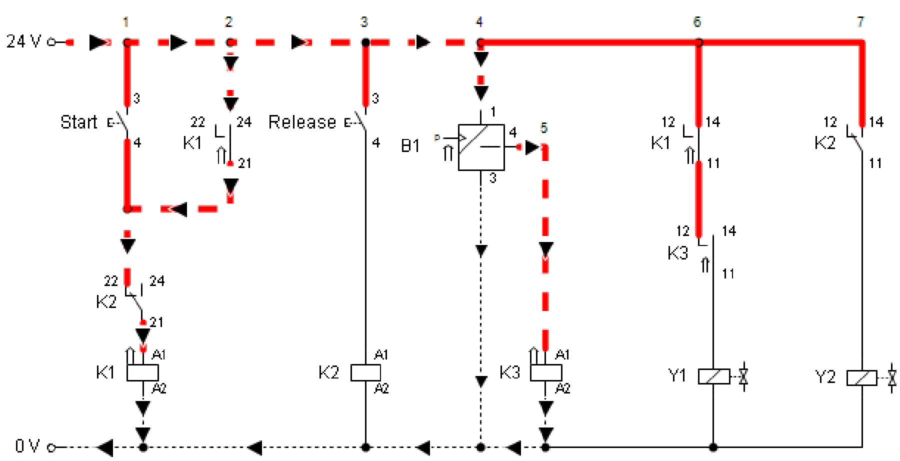
Conclusion:

It can be seen through this measurement that the system will supply compressed air to the vacuum generator only when it is really needed to do so, this saves a lot of resources over the course of time, it’s efficient and cost effective.

4. Controlled release of workpieces

Using FluidSIM create a circuit for controlling the release of a workpiece from a vacuum grip.





The components will be listed in the next page.

The list of components used:

- Electrical power supply (24V connection & 0V connection)
- Pushbutton (with dent switch)
- 2 changeover switches
- 2 Relays
- Valve solenoid
- Compressed air supply
- Air service unit
- 3/2 monostable valve with solenoid and manual override
- Pressure control valve with manometer
- Vacuum generator 05 H / 05 L
- Pressure gauge
- 2 vacuum efficiency valves
- 2 suction cups
- Pneumatic pressure sensor
- Check valve

Conclusion:

It can be seen through this circuit that a flow control valve can be used to control the compressed air going to the suction cups to remove the grip, adjusting the flow control valve will determine the rate of release. The spring-loaded check valve is what allows the compressed air to pass to the flow control on the condition of the worker pressing the “Release” switch to send a signal for the valve with “Y2” solenoid to activate and supply the compressed air.