

POLITECNICO DI MILANO

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Master degree in Mechanical Engineering

SOLENOID VALVES: LEAKAGE TEST ANALYSIS



POLITECNICO
MILANO 1863

Advisor: Dr. Diego Scaccabarozzi

Co-Advisor: Eng. Christian Cannas

Master degree thesis of:

Stefano Vitali

ID Number: 854326

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ABSTRACT

The thesis describes a project carried out in Ode S.r.l., a company that produces solenoid valves. The performed activity starts from the company's need to review and optimize some of the carried out processes. In particular, the work focuses on the phase of leakage testing of the valves; the main objective is the standardization of the leakage testing with the aim of improving the quality of the control, keeping an eye on the company productivity. Starting from the analysis of the actual situation through a series of experimental tests, the main parameters of the leakage testing have been modified and related testing cycles created. The new cycles are tested and results compared with previous testing method on the basis of the variation of the number of processed valves with the new adopted testing cycles.

SOMMARIO

La tesi descrive un progetto svolto presso Ode S.r.l., azienda del territorio che produce elettrovalvole, e nasce dall'esigenza dell'azienda stessa di rivedere ed ottimizzare alcuni dei processi da essa svolti. In particolar modo il lavoro si concentra su quella che è la fase di collaudo delle valvole per verificarne la tenuta, avendo come obiettivo la standardizzazione di tale processo col fine di migliorarlo sia dal punto di vista qualitativo che da quello produttivo. Per fare ciò si è partiti dallo studio della situazione attuale, tramite una serie di prove sperimentali, tutti i parametri in gioco nel processo sono stati modificati e i relativi cicli di collaudo sono stati creati. I nuovi cicli sono quindi stati testati e i risultati confrontati con la situazione precedente valutando la variazione del numero di valvole che è possibile processare con i nuovi cicli adottati.

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1 INTRODUCTION

1.1 ODE S.R.L.

The project was developed in ODE S.r.l, an Italian leading company since 1960 in designing and manufacturing complete line of solenoid valves and pumps for vending, coffee machines, carwash, automation, medical, food & beverage, water control and chemical.

ODE is headquartered in Segrate, Milan, with the manufacturing plant in Colico; anyway the company has a footprint in all major countries through a distribution network able to reach any customer.

The company has always been at the forefront in the market thanks to the continuous innovation in products, process and research for customized solution. The recent acquisition by Defond Group, supplier of components for home appliances and various industrial application located in Hong Kong, has provided investments in specialized human resources and multinational technologies.

ODE quality is based on the platform of process control granting the elimination of variances, a computerized integrated system able to guarantee the conformity of products, the recording each production step able to ensure effective data analysis as well as a complete and efficient traceability of both components and finished products, always maintaining standards of high competitiveness in the marketplace. All the above allowed Ode to obtain the ISO 9001, UL, CSA, UR, VDE, NSF, PED and ATEX certifications.

The production plant of Colico, site where the project is developed, is composed by:

- Mechanical department where the sub-components are made through various process like turning, milling, welding and so on;
- Warehouse for the raw materials and sub-components purchased externally;
- Assembly department with different lines for the assembly and the testing of the valves, directly connected with the shipping department;
- Laboratory for different tests (mechanical, electrical, magnetic and so on) mainly for the development of new products;

- Workshop for the prototyping of new components and the study of the production cycles;
- Qualified departments like technical and production department, quality assurance, human resources.

1.2 WHAT IS A SOLENOID VALVE

As already mentioned, the main product produced by ODE is the solenoid valve, an element designed to regulate the flow of fluids whose opening and closing commands is entrusted to an electrical circuit. Depending on the supply state of the solenoid valve, the fluid is free to pass through the valve or it is blocked by isolating the inlet pipe and the outlet one. Figure 1-1 represents the cover of the company catalog where some of the products sold are presented; as it can be seen the product, while remaining conceptually the same, can have multiple variants from different points of view: dimensional, operating principle, material and so on.



Figure 1-1: Some example of solenoid valves produced and sold by ODE

1.2.1 Main components

From the mechanical point of view (see Figure 1-2), the standard product is composed by two **pipes**, one for the input and one for the output, that communicate through an hole which can be obstructed or not, allowing or preventing the fluid passage. The component which is entrusted with the task of blocking the **orifice**, the hole described above, is a **shutter** clamped in a cylinder called **plunger**, which has the ability to move inside a guide tube called **armature tube**. This armature tube, on one side is joint to a component called **fixed core**, while on the other side is screwed to the **body** of the valve which contains the mentioned pipes. In the inner part of the plunger is inserted a **spring** that pushes the shutter. The set of armature tube and fixed core is called

"**complete armature tube**" while the set of plunger and shutter is called "**complete plunger**".

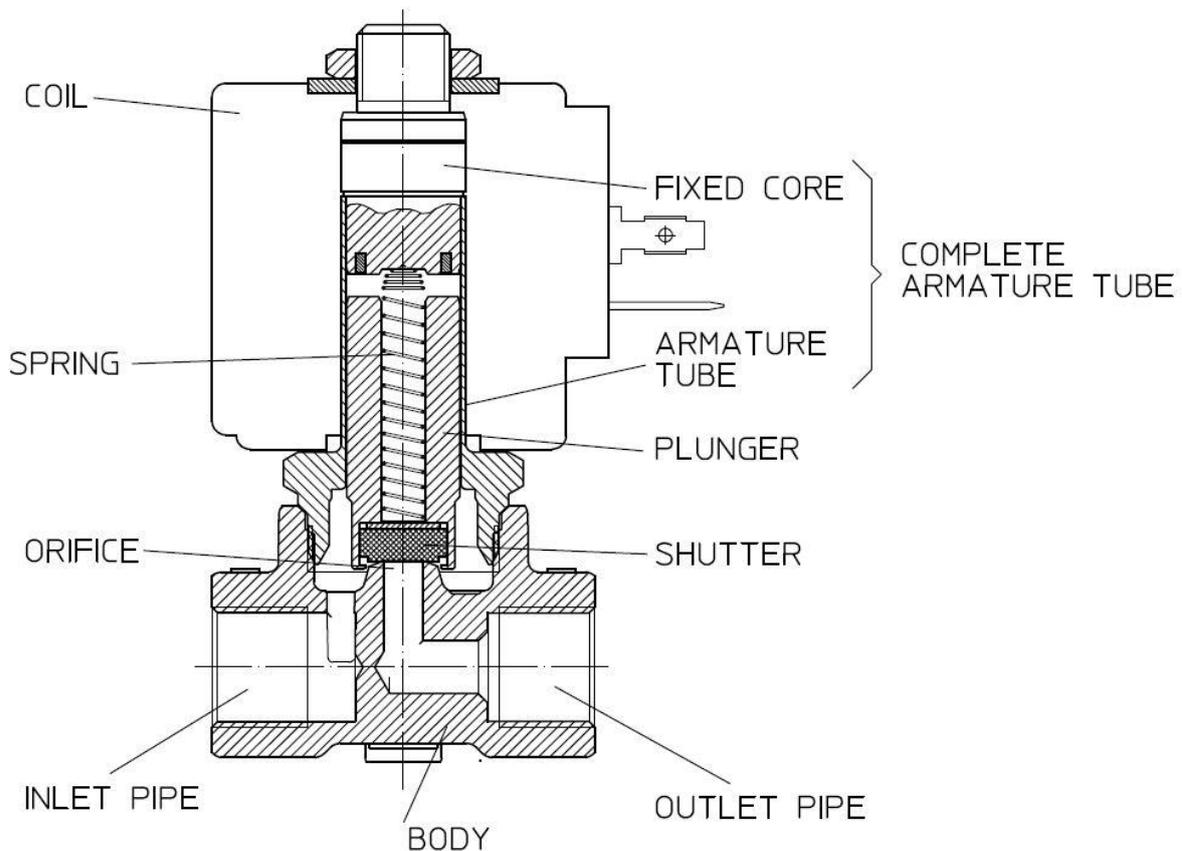


Figure 1-2: View of a section of the solenoid valve with the indication of main components

To complete the solenoid valve there is the electrical part, which essentially consists in a **coil** mounted around the armature tube and fixed to it by means of a nut. The coil consists of a **copper wire** wrapped around a **spool**, inside which the armature tube will be inserted; everything is isolated from the outside by means of a **metal bracket** and a **plastic encapsulation**. From this coil three **contacts** start, two for the power supply and one for grounding. In the section in Figure 1-3 all the components and their layout are shown.

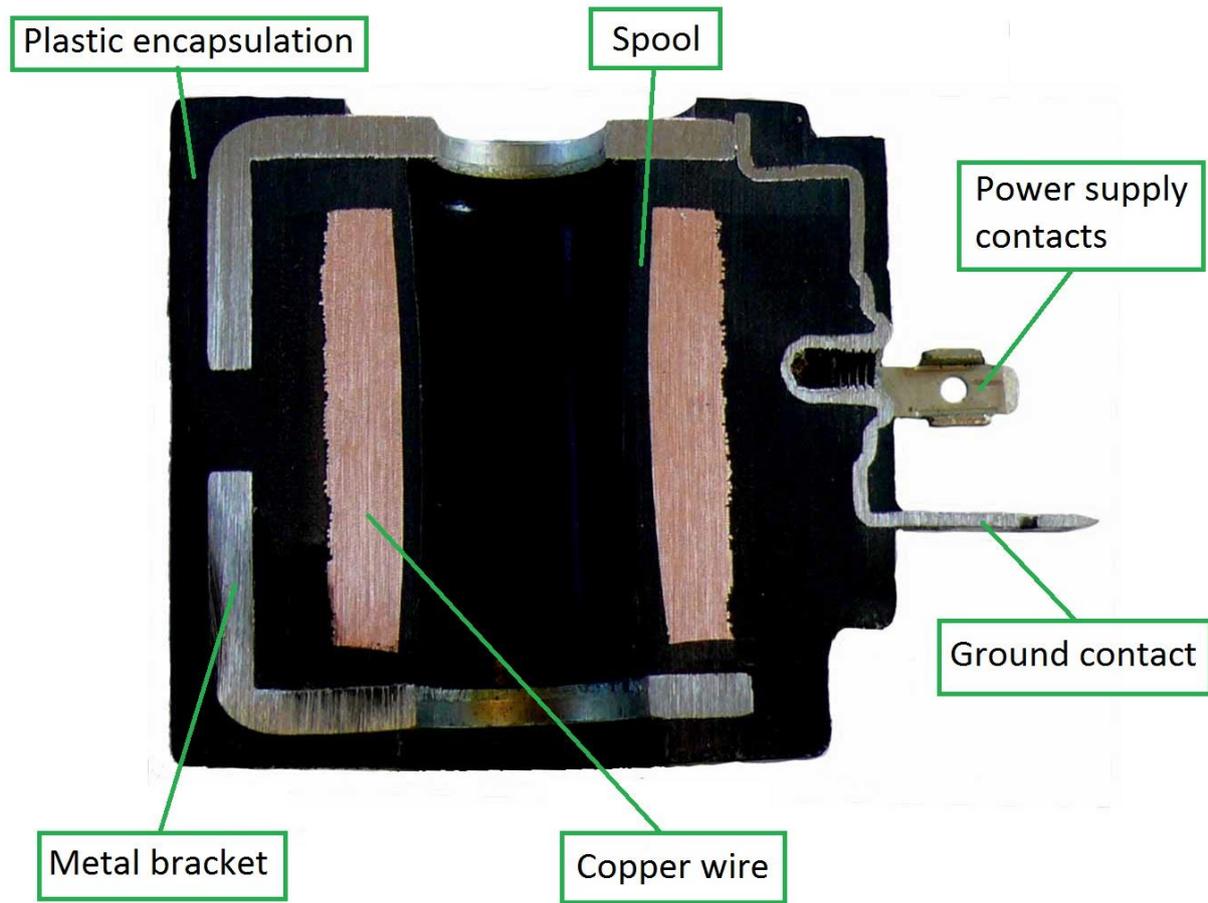


Figure 1-3: Vertical section of a coil

1.2.2 General working principle

For a normally closed solenoid valve, that means with a configuration such that the passage between input and output is closed when the valve is disconnected, the operating principle is: the complete plunger is pressed against the orifice mainly by two different forces, an elastic force due to a spring and the pressure of the inlet fluid. When the coil is fed with a certain voltage, the current starts to flow within the wire and this generates an induced magnetic field. The lines of this field within the spool are parallel to the axis of the coil while out of this they close due to the metal bracket. In this way the plunger, made up of ferromagnetic material, is attracted by the fixed core, also of ferromagnetic material, so as to free the passage of the orifice. Obviously it is necessary that in the design phase the configuration is made so that the electromagnetic force can overcome the sum of the two forces described above, i.e. elastic force and pressure of the fluid. Therefore, as long as the coil remains fed, the valve is open and the fluid can freely flow from the inlet to the outlet, as soon as the

power is removed, the electromagnetic force disappears and the valve closes. This, as said, is the normally closed valve. Instead, a different configuration can be achieved so that the valve is normally open by pushing a spring onto the plunger. In this case the electromagnetic force closes the plunger against the orifice and blocks the passage of the fluid. In Figure 1-4 you can see the operating diagram of a normally closed solenoid valve (on the left side) and a normally open (right).

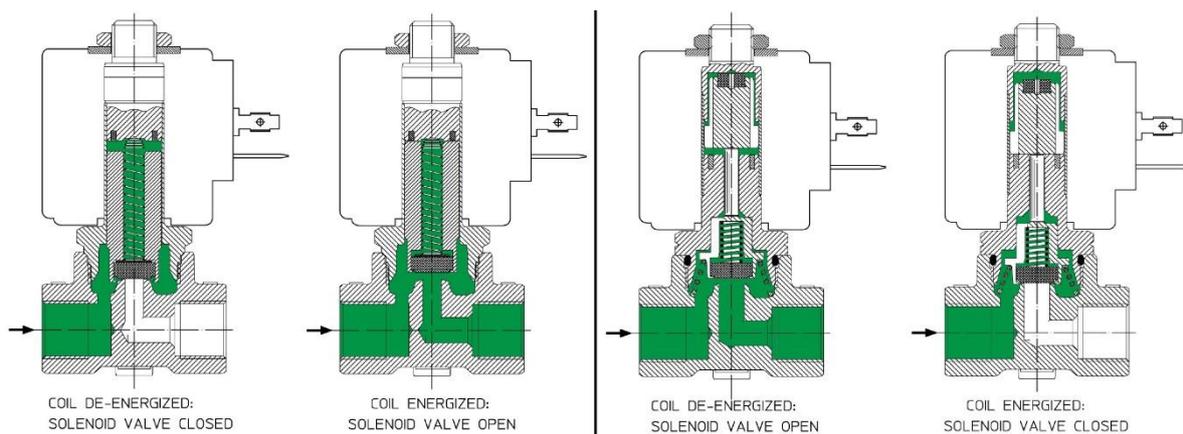


Figure 1-4: Working principle of a 2 way normally closed direct acting solenoid valves (on the left) and a normally open (on the right), the green zone means area occupied by the fluid

1.2.3 Different types of solenoid valves

What was described is the most general operating principle of a solenoid valve, without going too much into the details of the possible components or different operating modes. Actually, however, the possible solenoid valves are innumerable, just think that the company counts hundreds of different valve codes and that for each new customer's order the technical department can design a customized solution in relation to the specific requirements.

The different typologies may differ for various reasons, now we will present some examples. In addition to the already mentioned difference between normally open and normally closed, it is possible to distinguish the valves for the coil feeding type, i.e. DC or AC. The solenoid valves can also be divided between direct-acting solenoid valves (the operation of which was just described), solenoid valves with pilot control and combined operation solenoid valves; the latter two have a somewhat more complicated configuration since they are essentially composed by two valves (one is the main valve and the other is the pilot) but allow higher performances in some aspects such as

pressure and mass flow. Other differences can be related to orifice dimension, which involves different permissible flow rates, or may concern the fluid for which solenoid valves have been designed, such as air, water, freon, oxygen, and so on. Moreover another important valve classification can be made according to the material used for the body, the most common ones are brass, aluminum and plastic polymers, while complete armature tube and plunger are made in several variants of austenitic and ferritic stainless steels. Till now a two-way valve, one inlet and one outlet, has been described, but it is also possible to have a three-way valve in which, in addition to supply and use pipe, there is also a discharge fitting tube that in closed valve conditions is put into communication with the outlet. These are only the main variants of solenoid valves but actually there are a lot of more different types but it is not possible to explain the characteristics of all of these.

1.3 THESIS WORK

The thesis work at ODE plant of Colico is focused on the analysis of the solenoid valves testing systems. The main test performed, that will be also the object of the project, is the evaluation of the leakage of fluid which flows with a certain pressure into the valve. The purpose of the project is to revise the solenoid valve testing procedure in order to achieve an improvement from a production point of view of the current cycles. In addition, the work involves the introduction of a new software that facilitates the management of the testing process, simplifies its implementation and improves its traceability. Lastly, looking at all the collected data, a possible change in the existing testing plans is evaluated to gain benefits from a production point of view without however affecting the high quality standards of the company.

The starting point of the project is the definition of the current situation: description of the leakage test processes, analysis of the parameters used, evaluation of the current performances and definition of the main critical issues. At this point the work focuses on the study of products in the catalogue of the company in order to identify which ones are the most important from sales volumes point of view. These are now technically analyzed and divided into families specifically created thinking at the test cycles. Then different experimental studies are performed in order to collect data that will be the starting point for the creation of new cycles for an optimized testing procedure.

The initial study of the current situation would point out issues of the testing phase (if present) that represents a critical activity to be carefully studied in order to reach the best possible performances.

First of all, the number of different cycles used is very limited with respect to the huge variety of codes and so, the same cycle is used with very different products but effectiveness of the used testing procedure was never completely assessed. Moreover there is not a perfect relation between codes and basic cycles and this can be misleading in the test phase. In order to overcome these problems, during the project a reorganization of the testing cycles is made and the created cycles are collected in a database that resumes the coupling with each single code.

Moreover, an additional improvement to be obtained is related to the monitored parameters (i.e. the cycle times, the test pressure and the pressure decay limit) of the actual cycles. These are now set using the operators experience but no study has been up to now performed to evaluate their efficiency in evidencing the leakage phenomenon. So, in order to achieve the previous objective, a specific experimental study is planned and performed.

It has to be noticed that the definition of the time for the test cycle is a critical task because the time should be related to a tradeoff between two different needs, i.e. performing the test as fast as possible (short times preferred) and stabilization required to achieve reliable results (long times needed). For this reason, during the project a specific study regarding the definition of times is performed.

The intended work would allow improving the reliability of the new cycles results and would guide future changes of the testing procedure starting from the obtained results of the performed study.

2 LEAKAGE TEST DESCRIPTION

2.1 GENERAL SITUATION

The first step of the work involves the study of what is the current state of testing on the solenoid valves in the company.

ODE's procedure requires that at the end of the assembly phase, just before the shipping, 100% of the manufactured solenoid valves are tested to evaluate the sealing of the product. The aim of the leakage test is to check that the valve as a whole presents a leakage flow minor than an acceptable value, whether outwardly or through the pipes inside the valve. In particular, a standard solenoid valve has mainly three critical points that in most of the cases are responsible for a leakage in the valves (see Figure 2-1): the welding between the armature tube and the fixed core [1], the threaded coupling with OR between the armature tube and the body [2] and finally the closure of the shutter on the orifice to separate supply and use pipe [3]. Obviously it is possible, in very rare cases, that fluid leakage may occur at other points as it may be a micro-crack in a component or other material problems.

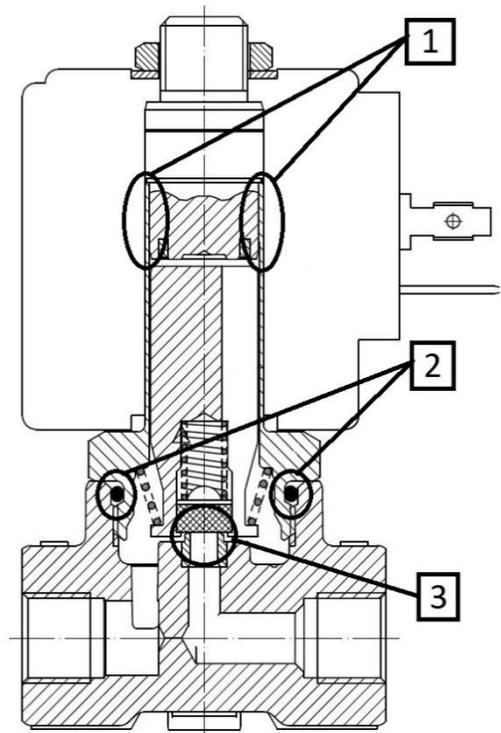


Figure 2-1: Solenoid valve section indicating the more important points from a leakage point of view

The company certifies each valve for a maximum flow loss value; for most of the products this value is 4 cm³/h. There are, however, cases where the acceptability limit is higher, as can be 10/20 cm³/h; this is valid for example for applications having as fluid water, whose greater viscosity with respect to the air makes the leak more difficult. Otherwise for some application, as it may be with freon, it can be possible that it is needed to guarantee more safely that the fluids will not leak; in these cases ODE is able to verify and guarantee on the valve a mass flow rate loss minor than 3 grams per year.

Leak testing can be done in a variety of ways and with the use of various tools. Historically, leak testing in the company was done with the aid of a water tank where the valve filled with pressurized air was immersed; in the case of valve leakage, air bubbles begin to form in the water and rise to the surface. These bubbles were observed by the operator and, depending on the size and frequency of these bubbles, it was possible to roughly determine the flow rate of the leakage and then assess whether to discard the valve or accept it as it is. This test method, performed as described, is qualitative and it is based on the operator's level of experience; furthermore it is difficult to automatize it and keep its results as a quality indicator of the production. Currently, this type of test has been largely replaced by the use of specific tools for measuring leakage, although it is sometimes used because it allows to see the precise point where the loss occurs in a rather straightforward and immediate manner.

The instruments currently used estimate the flow of loss according to two different principles:

- The most used instrument, as well as the one on which the thesis will be focus on, is an ATEQ leak tester (especially two different versions of the instrument are present in the company: ATEQ F520 and ATEQ F620). This instrument measures the flow of loss indirectly using a differential pressure decay measurement; in fact what it does is to fill the valve with air at a certain pressure, then the valve is isolated and after a certain time, the pressure inside is checked. In this way it is possible to calculate the pressure drop inside the valve and relate it to the flow exiting from the isolated system due to the leakage;

- The second instrument is a SNIFFER probe (ATEQ H6000) that is able to directly measure leakage flow when the valve is filled with a particular nitrogen and hydrogen mixture (95% N and 5% H). The use of this instrument requires a greater amount of time and experience because the sensor needs to evaluate all the points of the valve, paying particular attention to the above mentioned connections where leaks are more frequent. On the other hand, however, this instrument is necessary, thanks to its high precision and sensitivity (sensitivity $1 \cdot 10^{-7}$ atm cm³/s and measurement uncertainty $\pm 5\%$), when the maximum leakage is 3 grams per years.

So each valve is tested at the assembly line by an operator according to one of these methods and, based on the result, is discarded or accepted. The valves that pass the test are shipped to customers; instead the discarded valves are disassembled to evaluate, and solve, the origin of the loss. As it is easy to guess, this rework requires unplanned extra time for assembly and results in a decrease in productivity. Actually, the acceptance is based on the result of the testing which is related to both the tested valve and the testing cycle parameters. Thus, it is extremely important to evaluate correctness of the testing parameters in order to avoid misleading results which have direct impact on the company productivity.

2.2 LEAKAGE TEST WITH ATEQ

Now we will see more in the details the test with the ATEQ instrument, of which there are various models for both low (0 to 1 bar) and high pressures (1 to 30 bar) tests; in Figure 2-2 is shown the ATEQ F620 type, the latest model of these instruments. At the workbench of each assembly line there are several measuring instruments (typically 3 or 4) so that multiple valves can be tested simultaneously, for a total of about 40/45 instruments in the company.



Figure 2-2: ATEQ instrument for the differential pressure decay leak measurement

The process involves that the valve is fully assembled and, prior to being coupled to the coil, it is tested. For each type of valve there is a specially designed equipment for the locking of the valve by means of a quick coupling system. This also ensures that the valve is connected to the pressurized air supply pipe, controlled by the measuring instrument, which will fill the valve during the test.

Once the valve is locked, it is possible to perform the test which is carried out almost completely by the instrument, unless the cases when the valve needs to be opened or closed by means of a permanent magnet, task that is assigned to the operator. This test involves a cycle consisting of 5 different phases performed in sequence, as can be seen in Figure 2-3:

1. Phase 1, **Wait**: time needed for coupling the valve to the pneumatic system of the ATEQ;
2. Phase 2, **Fill**: period in which the input air at a certain pressure is opened until it reaches a state of equilibrium in which the valve is completely filled with pressurized air;
3. Phase 3, **Stabilization**: the pressurized valve is completely isolated and the system stabilizes, because of thermal and elastic phenomena it is possible that initially the pressure in the system will oscillate slightly;
4. Phase 4, **Test**: time in which the pressure drop (Δp) of the valve, always isolated, is measured; this pressure variation can only be due to a leakage, so this will be the key to assess whether the piece conforms to specifications or not;

5. Phase 5, **Dump**: concluded the test and evaluated whether the valve is compliant or not, the air is discharged and the valve uncoupled from the equipment.

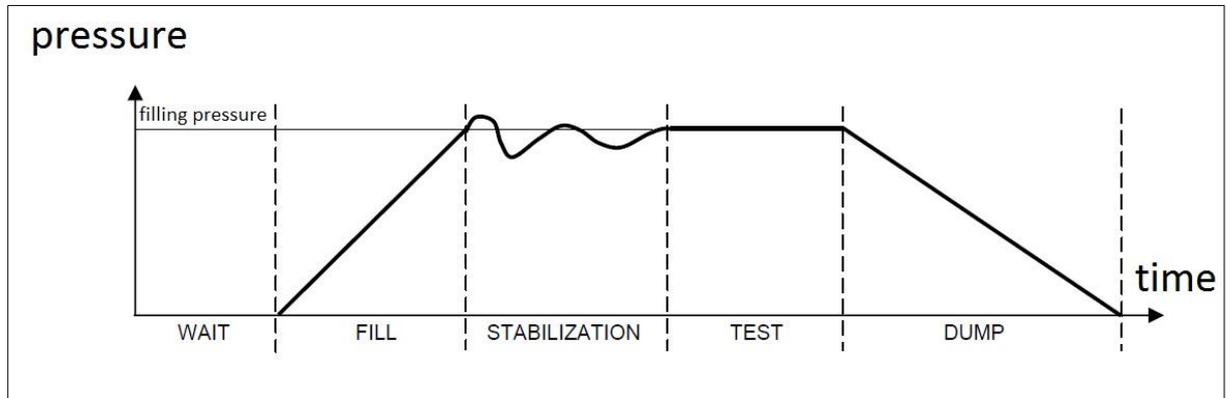


Figure 2-3: Leak test cycle for a solenoid valve using the pressure decay method

The basic parameters of the test cycle are the **times** of each phase, the air pressure with which the valve is filled (**filling pressure**) and the maximum **pressure drop** (Δp) that can be accepted. It has to be considered that during the discussion of the thesis this last parameter is expressed in two different ways: in term of absolute pressure drop [Pa] and in pressure drop in unit of time [Pa/s]. The only difference is that in the second case also the test time is considered, dividing the total pressure drop for the time of the test. Nevertheless the two way to express the pressure drop can be considered equivalent in the developing of the project.

These parameters cannot be the same for all the valves that are tested; this because the valve's volumes can be different and therefore the minimum fill time is automatically different or, as already mentioned, the accepted loss may vary and consequently also the drop in pressure allowed. For this reason, the ATEQ instrument allows to create different basic cycles, characterized by different parameters, and the operator can select the correct one according to the batch of valves to be tested. To help the operator in the cycle selection, a basic cycle summary module has been created; this shows the main parameters and some guidelines for each program.

Nowadays, the times of the different stages and the filling pressure of the air are the result of the experience accumulated over the years. Instead, the accepted pressure loss was initially obtained through an experimental evaluation with a sample loss. This evaluation allowed to relate a flow (i.e. 4 cm³/h previously mentioned, for example) with

the pressure drop measured by the instrument. However, this study had never considered the influence of the variables (filling pressure and filled volume) but it had just extended the results from the specific test with sample loss to all the operating conditions. For this reason, the parameters obtained were sometimes incorrect and it was therefore necessary to change them during time, based on practical experience.

2.3 KEY POINTS DISCUSSION

First of all, it is necessary to point out that the parameters of the current basic cycles (times and pressures) set on the ATEQ instruments have never been studied and analyzed according to a scientific approach, but are the result of the experience of the operators and of what has always been done.

Moreover, there is no unique relationship between the valve type and the basic test cycle, since for a certain valve, the operator has the freedom to choose between different opportunities. This can lead to a mistake in the testing phase, going to accept valves that are not within the limits of acceptability, but also a loss of productivity when choosing a cycle that is not the optimal one.

Furthermore these basic test cycles created during the years according to the needs and collected on the module previously mentioned are around 30. But, of these 30 cycles, only about 10 are really used on a continuous basis. This means that only few programs are associated with a large variety of different valves, covering a range of volume very high. For this reason is quite immediate to understand that the parameters of a cycle cannot be optimized for all the different valves that use the cycle itself.

Regarding the length of the test, it is easy to notice how the total cycle time is given by the sum of the times of each of the phases above described; it is therefore important that each phase lasts a time that is sufficient to ensure correct testing (for example valve filling or stabilization), but it is also as short as possible for minimizing the cycle time. This is even more important if you take into account the fact that, between all the operations carried out during assembly, the test is the bottleneck of the line. It is clear that speeding up this phase would directly lead to an increase of productivity of the department. The total cycle time is typically in the order of 25/30 seconds, which means that thousands of leak tests are performed in a working day; so even saving few

seconds in each cycle can result in substantial savings of time at the end of a working day.

Another aspect to underline is the fact that the maximum flow of leakage accepted for most of the solenoid valves produced by ODE is set at 4 cm³/h, a value well below what is the standard for competitors and for the suggestions of ATEQ itself, set to larger values as 40/60 cm³/h. Therefore, it could be interesting to verify whether this over quality of ODE is recognized and appreciated by customers or if, even raising this limit, the market would remain unchanged. In this case, it would be worth considering the idea of revising the limits of acceptability by calculating how many pieces less should be reworked, leading to a time saving for the assembly line and an increasing of productivity of the department.

Finally, it is important to notice that during the leakage test, almost always, the three main sealing points are simultaneously tested with the tightest limit we want to guarantee on each point. It should also be taken into account that the loss value evaluated with the instrument is the sum of all the losses in the tested valve, which means that the loss value X read on the ATEQ instrument may be due to three contributions equal each one to $X/3$ or, in the opposite case, due to a single concentrated loss. It is thus clear how the two situations described are very different one from the other and therefore should require a different action by the operator.

However, this aspect will not be further developed for the moment because a study concerning the addition of an automatic test line after the welding between the armature tube and the fixed core has already being carried out. This would allow to test at first the leakage of the welding bead and then, during the assembly, the leakage of the couplings armature tube-body and shutter-orifice with a higher limit of acceptability.

2.4 DATA COLLECTION FOR THE EVALUATION OF CURRENT PERFORMANCES

In order to evaluate the present situation different data are collected to monitor the situation regarding the leakage tests. The objective is to evaluate the number of retesting needed for different types of valves and in general for all the production line. In fact, whenever the test with the ATEQ instrument indicates a not acceptable value of loss, the valve cannot proceed, for the packaging and the shipping. In case of a

negative test, what is done differs mainly in two cases, depending on the value of the loss. If the loss (pressure drop indicated by the ATEQ instrument) is much higher than the acceptable limit, the valve is disassembled, cleaned with pressurized air to remove any dirt residual and, where necessary, some components are replaced; finally, it is reassembled and retested. If the loss is only slightly higher than the acceptable limit, what is commonly done is a second test without even disassembling from the equipment; this is done because it has been noted that in the case of consecutive tests on the same piece, the loss value is lowered and finally falls within the range of acceptability. If in the first case we can talk about a qualitative problem related to the machining of the pieces or their assembly, in the latter case the problem lies in the testing parameters (as an instance, uncompleted stabilization) and so, a benefit can be reached redesigning the testing parameters.

In order to see better the effect of what is just said an experiment is performed, i.e. several identical tests were performed consequently in time and looking at the value of the pressure drop on the ATEQ. This value starts to decrease at each test reaching a plateau whose value is around 30% less than the starting one, as can be seen in Figure 2-4. This issue is due to the deformations of the components and some thermal phenomena.

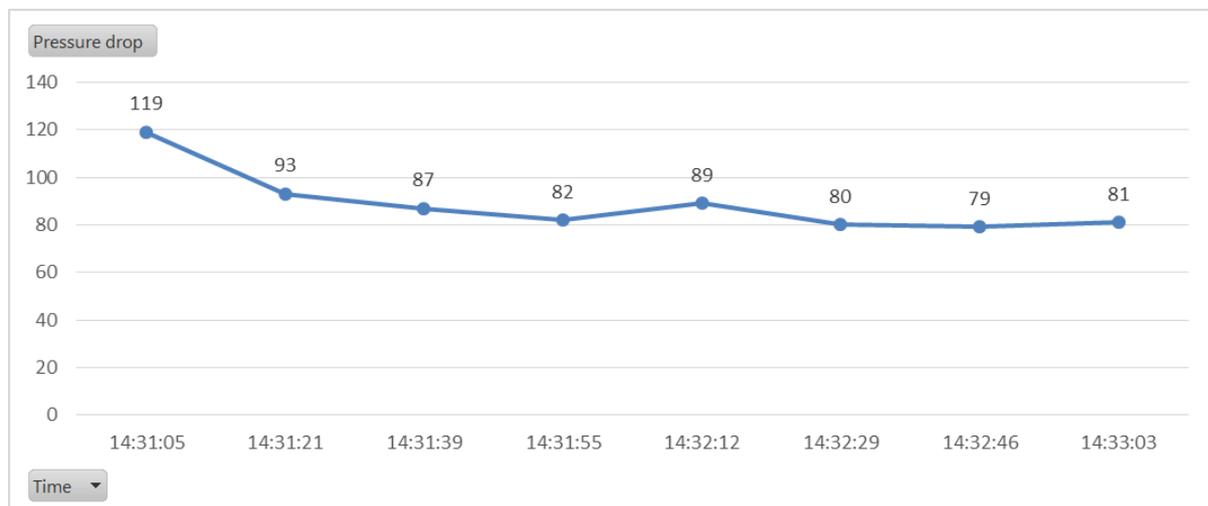


Figure 2-4: Pressure drop [Pa] of tests in quick sequence

The need of all the re-tests, whether they are due to quality problems or test design, means that for each batch the number of tests performed on the valves is greater than the nominal amount of the valve in the batch itself. Measuring what is the percentage of retesting is therefore an indication from the point of view of the quality of the

assembled products and of the measuring system but also, more interesting from our point of view, an information about what is the loss of productivity due to all those tests that are consequently performed.

The picture that will be outlined will be useful to describe more accurately the current situation but also set the basis for a comparison to be performed at the end of the work to evaluate the impact of the suggested variations. Data were collected in four different acquisitions that will be described in the next subchapters.

2.4.1 Analysis 1: statistics for valve codes

For this data collection, we exploit a functionality of the ATEQ instruments that is the possibility to record internally the data of carried out tests. For each basic cycle in memory, the instrument shows the total number of tests performed, the number of accepted pieces, the discarded ones and the alarms.

So for the campaign it is planned to monitor some specific batches, chosen in agreement with the responsible of the assembly department. What is done for each batch is:

- Reset results data saved on ATEQ machines just before batch testing begins;
- Read the statistics at the end of the batch to find only the records of that specific batch;
- Write down all necessary data on the specific module created shown in Figure 2-5, in this module there is a first part to collect the main information regarding the batch under investigation and a second part for the record of the results of each ATEQ instrument, in particular what is reported is the total number of performed test (TOT), the number of positive ones (PB), i.e. with a value of pressure decay acceptable, and the number of negative ones (ST);

General info about Batch and Workstation				
Date:	Batch N:		Quantity:	
N. Workstation:	Solenoid valve code:			
Test statistics				
	Ateq 1/Progr:	Ateq 2/Progr:	Ateq 3/Progr:	Ateq 4/Progr:
TOT				
PB				
ST				

Figure 2-5: Module for the collection of the leakage test's statistics

All the collected data are now dragged onto an Excel sheet to allow an easier analysis. What it is done is to merge all the data that are related to the same valve code. Then for each of them, starting from the total number of tests, it is calculated the percentage of the tests that gives a positive outcome (that means a value of pressure drop lower than the maximum accepted one). The results of this operation are shown in Table 1.

Valve codes and Programs	Sum of leakage tests	Average % of positive tests
21JP1_V	1032	98,49%
2A	1032	98,49%
21PW3_V	453	84,11%
11A	453	84,11%
21WA4_B	409	95,82%
11A	203	93,10%
12A	206	98,54%
31A1_RV	8546	80,90%
1A	4577	77,84%
4A	3969	83,97%
31A1_VV	278	74,25%
1A	146	71,23%
1A (conM)	132	77,27%
31JN1_VV	433	92,11%
2A (13)	224	93,30%
2A (14)	209	90,91%
31JP6_VV	5407	85,19%
1A (11)	2968	87,77%
1A (12)	2439	82,62%
31JPS_VV	1351	92,91%
2A (13)	694	94,96%
2A (14)	657	90,87%
TOTAL	17909	87,99%

Table 1: Resume of the results obtained with the analysis 1

Here we can see the 8 different valve codes (21JP1_V, 21PW3_V...) with the number of tests that are evaluated and the percentage of the positive ones. For some types of valve more than one test is needed, so also the results are divided on the two different standard tests (i.e. 11A-12A or 1A(12)-1A(13)...). In the last line, instead, the mean values of all the tests studied are presented. They say that on almost 18'000 cycles, around 88% of them has given a positive result. This means that the 12% of the performed tests needs an additional try, giving rise to a waste of time and productivity.

On one hand this type of acquisition is useful because it gives a direct idea of the percentage of positive and negative tests, also divided for each specific valve code. On the other hand this analysis has two problems: the first one is that it's quite time

consuming because it's needed to clear manually the memory of the instrument before each batch and then read, always manually, the results at the end; the second one is that we know which tests are positive and which ones are negative but we don't know the exact value of the pressure drop measured by the instrument. This means that for the negative tests we don't know if the pressure drop is only slightly higher than the limit or it is far greater. So, to overcome these problems, additional data acquisition and analysis have been performed.

2.4.2 Analysis 2: statistics for basic cycles

This analysis exploits another option that the latest version of ATEQ instruments has, that is the possibility to save on a USB pen all the information regarding the test each time the test is run. The stored data are: name and number of the basic cycle, result of the test (positive or negative), pressure drop measured, filling pressure, date and hour; all this information are saved in a row of a txt file. The problem of this analysis is that the data are not connected in any way to the type of the valve but they are related only to the basic cycle.

For this reason, at first, it was decided to collect data from different assembly lines; in this way we cope with different types of valves giving a more general picture of the actual situation. In particular the first analysis is done taking into account the results coming from different assembly lines in the department, the so called line 3, line 4 and line 5.

As shown in Table 2, the total number of leakage tests evaluated is equal to 12488, of these the 86.39% gives a positive result (PB), the 12.28% gives a value of pressure drop not acceptable (ST) and the remaining 1.33% is related to an alarm of the instrument (AL) that can be due to a filling pressure too high or too low, or a manual stop of the cycle before it is completed.

Result of the test	Number of Occurrences	% of Occurrences
(AL)	166	1,33%
(PB)	10789	86,39%
(ST)	1533	12,28%
TOTAL	12488	100,00%

Table 2: Macro-results of analysis 2

It is interesting to notice that the percentage of positive results is similar to the one identified by the previous testing (see Table 1).

The obtained results are related to all the different lines and basic cycles.

Instead, if we want to look more into the details of what is the situation for each line and cycle, the Table 3 gives a more detailed picture of the actual situation.

N.Line	BasicCycle Result	Number of Occurrences	% of Occurrences
3			
	1A		
	1A(AL)	4	0,28%
	1A(PB)	1256	88,02%
	1A(ST)	167	11,70%
	2A		
	2A(PB)	651	95,31%
	2A(ST)	32	4,69%
	TE		
	TE(AL)	1	14,29%
	TE(PB)	3	42,86%
	TE(ST)	3	42,86%
4			
	1A		
	1A(AL)	9	0,26%
	1A(PB)	2794	80,75%
	1A(ST)	657	18,99%
	4A		
	4A(AL)	13	0,84%
	4A(PB)	1148	74,55%
	4A(ST)	379	24,61%

N.Line	BasicCycle Result	Number of Occurrences	% of Occurrences
5			
	11		
	11(AL)	11	1,56%
	11(OK)	607	86,34%
	11(ST)	85	12,09%
	12		
	12(AL)	4	0,63%
	12(OK)	608	96,20%
	12(ST)	20	3,16%
	13		
	13(AL)	18	5,41%
	13(OK)	311	93,39%
	13(ST)	4	1,20%
	14		
	14(AL)	5	1,66%
	14(OK)	275	91,06%
	14(ST)	22	7,28%
	1A		
	1A(AL)	32	4,53%
	1A(OK)	634	89,80%
	1A(ST)	40	5,67%
	2A		
	2A(AL)	67	2,49%
	2A(OK)	2502	92,84%
	2A(ST)	126	4,68%

Table 3: Detailed results of analysis 2, divided by number of line and name of basic program

Here we can see again the percentage of positive and negative tests but divided for name of cycle and number of line. For example if we look to the program 1A, we can see that on line 3 it has a percentage of positive test equal to 88% but this index becomes 81% and 90%, on line 4 and 5, respectively. This difference implies that the

productivity of the same program can be different, due to the fact that each assembly line is specialized in a particular group of valves.

Now, what we did is to exploit the most interesting feature of this data collection that is the possibility to store the exact value of the pressure drop for each cycle. In this way we know the number of positive and negative tests and the distribution of the measured pressure drops in each test. To see in an immediate way this distribution, what we can do is to plot on an X-Y graph the pressure drop VS the number of occurrences. In this passage the results have been divided according to the different basic cycles from which have been taken, because each cycle is used for a specific situation so it is reasonable to think that the data will be distributed in a different way.

The graphs related to the basic cycles 1A, 2A e 4A are reported below in Figure 2-6, Figure 2-7 and Figure 2-8 (to facilitate the readability of the graph, the X axis is cut at certain value, not showing too high values of pressure drop that anyway have an occurrence very low).

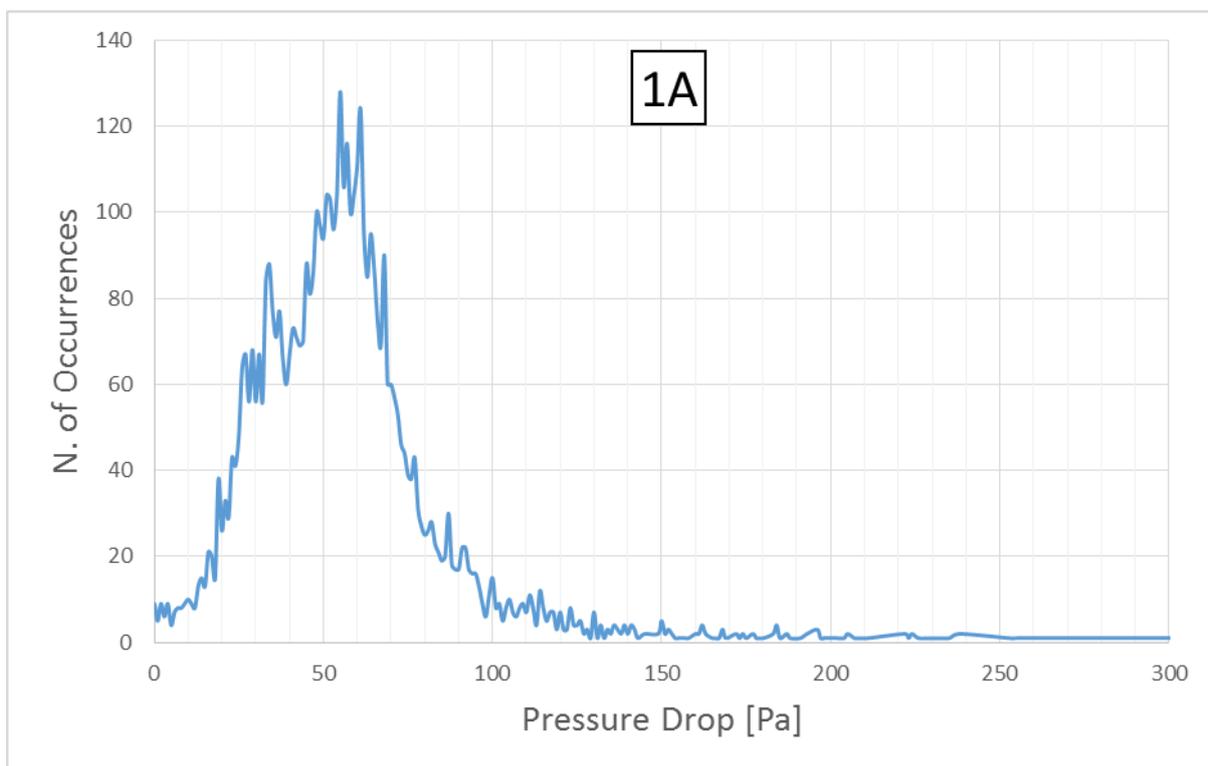


Figure 2-6: Distribution of data relative to cycle 1A

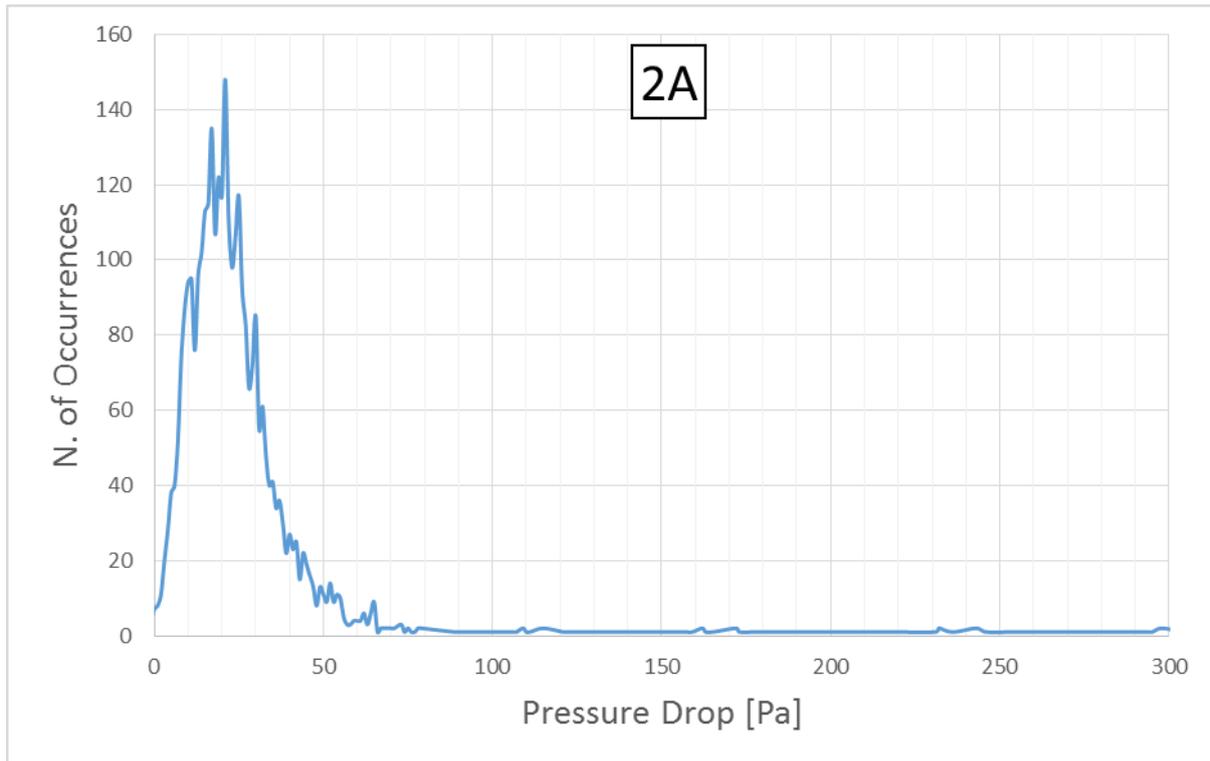


Figure 2-7: Distribution of data relative to cycle 2A

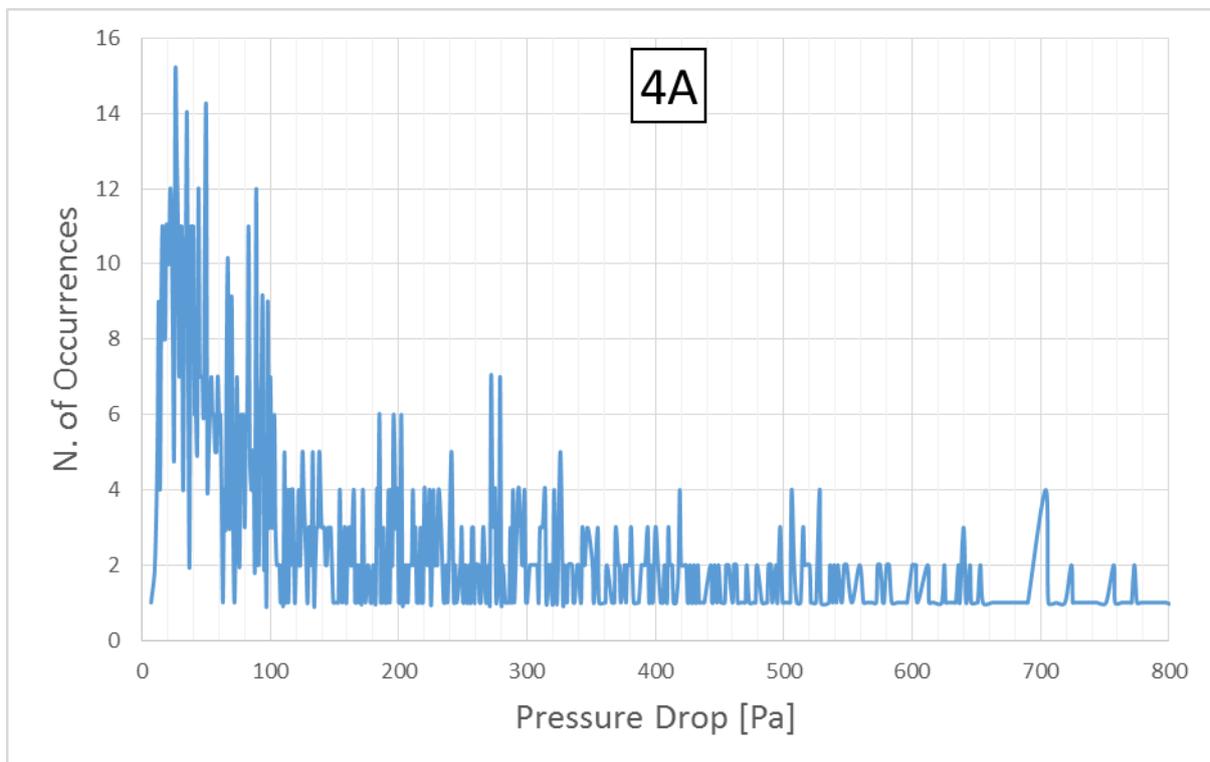


Figure 2-8: Distribution of data relative to cycle 4A

Measured average and standard deviation of the pressure drops have been computed for the tested cycles; it can be noticed that the average is higher in 1A (around 60 Pa)

than in 2A (around 20 Pa). Pressure standard deviation is about 28 Pa and 24 Pa for tests 1A and 2A, respectively.

The data in case of cycle 4A, instead, are more spread over a wide range of pressure drop, this is probably due to the nature of this leakage test aimed to verify the sealing between the shutter of Ruby or Teflon (very hard materials) and the orifice; this type of coupling always presents some leakage that is not repeatable. Average and standard deviation resulted respectively in 300 and 440 Pa, a further indication of the high variability of this type of test.

The possibility to store and analyze the value of the pressure drop gives another important benefit, which is the possibility to quantify how many tests present a value of pressure loss higher than the accepted limit. As already said, in case of a value of pressure drop slightly higher than the limit what is commonly done is to re-test the valve immediately, without any further action. This means that the repetition of the test represent a loss of time in the company productivity because the valve can be considered good at the first attempt. Anyway, knowing the distribution of pressure drops for each cycle, it is possible to know in advance the impact on the percentage of positive and negative tests of the modification of the maximum pressure decay accepted, so increasing this value we will find an increase of the number of positive test and the opposite decreasing the limit. An example of this possible analysis is reported in Table 4 where, for example, it is hypothesized to increase the limit of cycle 1A from 80 to 90 Pa, gaining an increase of positive tests of 4% on the total; instead a decrease from 60 to 55 Pa in cycle 2A brings to a decrease of 1% of the positive tests. This poses the question about how to set the threshold value for the testing, problem also related to the over quality approach followed in ODE.

Cycle	N. of tot tests	Actual limit [Pa]	N. of positive tests	% of positive tests	Hp of new limit [Pa]	N. of test potentially positive	New % of positive tests	% difference
1A	5593	80	4684	84%	90	4903	88%	4%
2A	3378	60	3153	93%	55	3135	93%	-1%
4A	1540	400	1148	75%	400	1148	75%	0%
11	703	80	607	86%	90	632	90%	4%
12	632	80	608	96%	90	611	97%	0%
13	333	60	311	93%	55	306	92%	-2%
14	302	60	275	91%	55	275	91%	0%
TOT	12481		10786	86%		11010	88%	2%

Table 4: Analysis of the impact of the variation of acceptability limits on the percentage of the positive tests

2.4.3 Analysis 3: influence of the filling time

During the study of the leakage testing phase it is noticed an important relevance of the filling time, for this reason another analysis has been performed for direct acting 3-way normally open valves, called 5578. These valves require, as all the 3-way valves, a double leakage test: one with the valve open to verify the leakage of the welding, of the mechanical coupling between armature tube and body and the sealing of the shutter on the orifice of the third way; the other with the valve closed to verify the sealing of the shutter on the main orifice. Now, the typical procedure for the leakage test is to check the valve using in both of the cases the basic cycle called 1A, before putting a permanent magnet around the armature tube (so to have the valve closed) and then remove the magnet and test the valve open. For the basic cycle 1A the main parameters are: filling pressure equal to 15 bar, filling time of 7 s, stabilization time of 11 s and test time of 4 s and finally a maximum pressure drop accepted equal to 80 Pascal.

To evaluate the actual situation, first experimental campaign is performed using the classical set-up of the test; the results are shown in Table 5 where test A represent the test with permanent magnet around the armature tube and test B the one without magnet.

Test Result	N. of Occurrences	% of Occurrences
A	492	
(AL)	5	1,02%
(PB)	456	92,68%
(ST)	31	6,30%
B	541	
(AL)	1	0,18%
(PB)	420	77,63%
(ST)	120	22,18%
TOTAL	1033	

Table 5: Macro-results of leakage tests for valves 5578

It can be noticed that for the first test, the percentage of positive results is quite good (around 93%) instead for the second test, only the 78% of the tests give a positive result, a value that for sure has a strong impact on the productivity of the department.

Now the idea is to modify the times of the cycle and look the results. It is decided, in agreement with the responsible of the department, to try to increase the filling time; for test A, a situation with filling time equal to 10 s is studied instead for test B two different situations are evaluated: with 9 and with 10 s of filling time. Again the results are collected and reported below in Table 6:

Test	N. of	% of
Times	Occurrences	Occurrences
Result		
A		
10_11_4	484	
(AL)	3	0,62%
(PB)	471	97,31%
(ST)	10	2,07%
B		
10_11_4	517	
(AL)	7	1,35%
(PB)	449	86,85%
(ST)	61	11,80%
9_11_4	526	
(AL)	7	1,33%
(PB)	427	81,18%
(ST)	92	17,49%
TOTAL	1527	

Table 6: Macro-results of leakage tests for valves 5578 after the modification of filling time

It can be seen that in both of the cases (A and B) the percentage of positive results increases going in one case from 93% to 97% and in the other case from 78% to 81% or to 87%, depending on the filling time increase.

The first important conclusion is that the actual filling times are not sufficient to reach a situation of complete stability and so a part of the pressure decay during the test is due to stabilization phenomena. This is verified because the mean pressure drop decreases if the filling time increases and the only reason for this change, is the fact that the air in the valve was not completely stable when the test started.

The times of the cycle, as already discussed in the introduction of the test parameters, have to be chosen on the basis of a tradeoff between the need to reach a situation of stability and the will to increase the productivity reducing the times. For this reason it

is interesting to study if the increase of the filling time done before represent an improvement of the productivity, to evaluate if it will be convenient or not.

From the study of the situation with the actual times (7 s of filling, 11 s of stabilization and 4 s of test), counting the number of test performed in a certain time, the total cycle time (that consider in addition to the previously mentioned times also the time needed for the manual operation of coupling and decoupling the valve with the equipment) can be calculated on average. This time for this specific test and valve is equal to 32 s. Now it is considered a working day of 8 hours, which are equivalent to 28'800 seconds; dividing this value by 32 we obtain the maximum theoretical number of cycles that can be done in a day, equal to 900. Considering that in a line there are usually 4 ATEQ instrument working in parallel, finally we find that the line has a capability of 3600 cycles per day. To conclude the analysis we have to calculate the number of good valves that the line produces, and this is just the multiplication of the cycles per day times the percentage of the positive test. For the example considered the positive tests are equal to 92.68% of the total and so the throughput of the line, considering only the specific test of the specific valve, is 3336 units per day. Now repeating the procedure for all the alternatives considered, both for test A and for test B, it is possible to calculate the throughput in each case and evaluate which is the more convenient. This procedure is resumed in Table 7 below.

Test A			Test B			
Fill time [s]	7	10	Fill time [s]	7	9	10
Cycle time [s]	32	35	Cycle time [s]	32	34	35
Cycles/day	3600	3291	Cycles/day	3600	3388	3291
% positive tests	92,68%	97,31%	% positive tests	77,63%	81,18%	86,85%
Good pieces	3336	3203	Good pieces	2795	2751	2859

Table 7: Comparison of the productivity of cases with different times of the test

On the left, for the test A we can see that increasing the fill time, even if the percentage of positive tests is increased, the good pieces produced in a day will decrease and so also the productivity. For this reason it is more convenient to accept to retest some more valves rather than increase the time of all the tests performed. A different situation can be seen on the right for the test B, for which the increase of the time will lead to an increase of the overall productivity. This analysis allows to evaluate the cost and the benefits of each possible configuration in order to find the optimal one in terms

of good pieces produced and so evaluate the impact of the parameter value on the company productivity.

2.4.4 Analysis 4: statistics of a critical code

The last data analysis is focused on another specific type of valve, called 4628, which has been found to be a problem in the phase of testing due to the numerous retesting needed. The data relative to a batch are collected and analyzed to study the real performances of the leakage tests on these specific valves. Also this valve is a 3-way valve and so it needs two consecutive tests, with valve open and with valve closed, that are called respectively cycle 13 and 14. The Table 8 resumes from a macroscopic point of view the results of the analysis on both of the tests.

Cycle name Result	N. of Occurrences	% of Occurrences
13	1111	
(AL)	1	0,09%
(PB)	851	76,60%
(ST)	259	23,31%
14	844	
(AL)	3	0,36%
(PB)	764	90,52%
(ST)	77	9,12%
TOTAL	1955	100,00%

Table 8: Results of the analysis relative to the two different leakage tests of the valve type 4628

The results confirm that the percentage of the positive tests of the cycle 13 is very low, around 75% which means that one fourth of the tests give a negative result and so they need additional analyses.

But what is more interesting to study is how the negative tests are distributed, in terms of pressure drop. In order to do this we can perform the same analysis of the analysis 2, in which is studied the impact of the variation of acceptability limits on the percentage of the positive tests. All these information are collected in the Table 9, where two different cases are presented: the effect of increasing the pressure drop limit from 80 to 90 Pa and from 80 to 100 Pa.

Cycle	N. of tot tests	Actual limit [Pa]	N. of positive tests	% of positive tests	Hp of new limit [Pa]	N. of test potentially positive	New % of positive tests	% difference
13	1111	80	851	77%	90	944	85%	8%
14	844	80	764	91%	90	792	94%	3%
TOT	1955		1615	83%		1736	89%	6%

Cycle	N. of tot tests	Actual limit [Pa]	N. of positive tests	% of positive tests	Hp of new limit [Pa]	N. of test potentially positive	New % of positive tests	% difference
13	1111	80	851	77%	100	994	89%	13%
14	844	80	764	91%	100	813	96%	6%
TOT	1955		1615	83%		1807	92%	10%

Table 9: Analysis of the impact of the variation of acceptability limits (with two different values: 90 and 100 Pa) on the percentage of the positive tests for the valves 4628

In both of the cases, it can be seen that the increase of the limit brings to a substantial increase of the percentage of the positive tests, up to over 10%. This means that a lot of the negative tests have a pressure drop included between 80 and 100 Pa, that cannot be considered a real valve rejection because in most of the cases, the same valve will pass the test after some repetitions without any further action. From production volumes point of view this means that increasing the limit of 12% (from 80 to 90 Pa) the line will be able to produce around 300 units more per day. This number for the 8 main lines of the department, means more than 2000 additional pieces produced each day with respect to the actual ones. Of course if the increase of the limit is higher (25% like in the second case) also the number of extra pieces is higher: 470 units/day for each line or 3700 units/day for the whole department.

This highlights again the need of clearly define the limits for the acceptance, parameter that seems to be critical for the selection between positive and negative result in the valve testing.

3 CLASSIFICATION OF THE SOLENOID VALVES

3.1 IDENTIFICATION OF THE PRINCIPAL VALVES

The first step in the product analysis phase is the evaluation of all the solenoid valves produced by the company in order to group them into families that are characterized by the same testing procedure and similar internal volumes. The number of different solenoid valves produced by ODE, however, is in the order of thousands and so it is impossible to perform an extended analysis considering all the codes.

It is therefore necessary to evaluate those products which, from the point of view of the quantities produced, are of the utmost importance. To do this, data on products sold in the year 2016 are taken as a starting point. These are then processed to significantly reduce the number of codes that will be analyzed. First, all those codes that belong to the same product's family are aggregated; later, those products that do not require testing, such as spare parts, or products different from solenoid valves, or those for which testing is not made using ATEQ, are not taken into account. Following these operations, the number of codes goes from 1'583 to 351, for a total of 2,008,248 sold units.

At this point a Pareto analysis, as shown in Figure 3-1, is performed to evaluate the distribution of such data. Using this analysis, it can be seen that over 90% of the units sold (92% to be precise) are due to only 89 codes, equal to 25% of the total codes. It is therefore considered satisfactory, at least for the first phase of the work, the analysis of these 89 codes, which represent the solenoid valves of which at least 3,000 units were sold during the 2016.

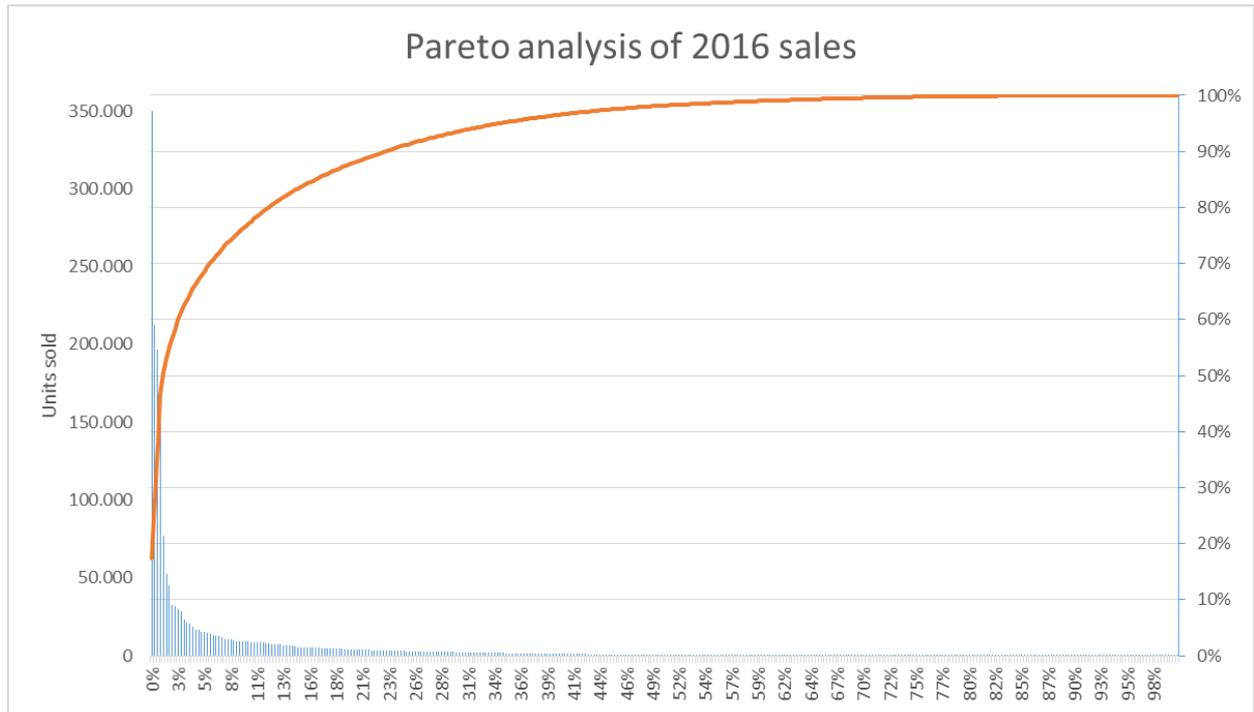


Figure 3-1: Pareto analysis that represent the sales of the solenoid valves during the 2016

3.2 CALCULATION OF VALVES VOLUME

Now, for the 89 codes previously mentioned, it is necessary to evaluate the internal volume of the valve, which is the area that will be filled by the pressurized air during the test with the ATEQ instrument. This will be an important parameter because it will determine the timing of the test cycle (filling and stabilization) but will also affect the pressure loss accepted with the same flow limit.

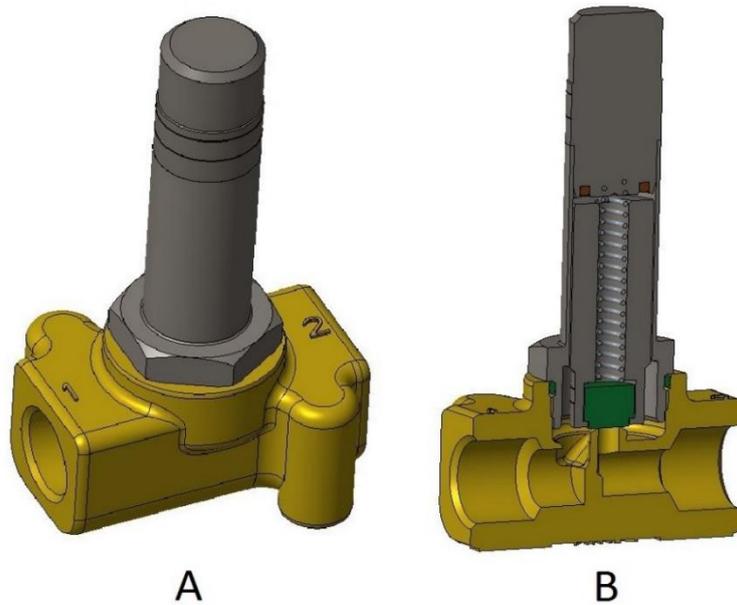


Figure 3-2: 3D model of a valve in particular: external view (A) and sectional view (B) of a solenoid valve JN1

For the calculation of the volume, it is used the 3D design software Creo Parametric 3.0, which allows, starting from the valve assembly, to generate the negative and calculate the volume. For this specific project it is thought to calculate the volume divided into two components, the first one from the entrance to upstream of the orifice while the second downstream of this. In turn, the volume upstream of the orifice is calculated as the internal volume of the inlet pipe and armature tube minus the volume of the complete plunger contained.

For clarity, see Figure 3-3, which clearly shows the different components valued to obtain the inner volume of the valve:

- Volume 1: represents the internal volume upstream of the orifice, which includes the inlet pipe and the armature tube;
- Volume 2: represents the inner volume downstream of the orifice, that is simply the outlet pipe;
- Volume 3: it is related to the complete plunger (plunger, spring and shutter) located inside the tube

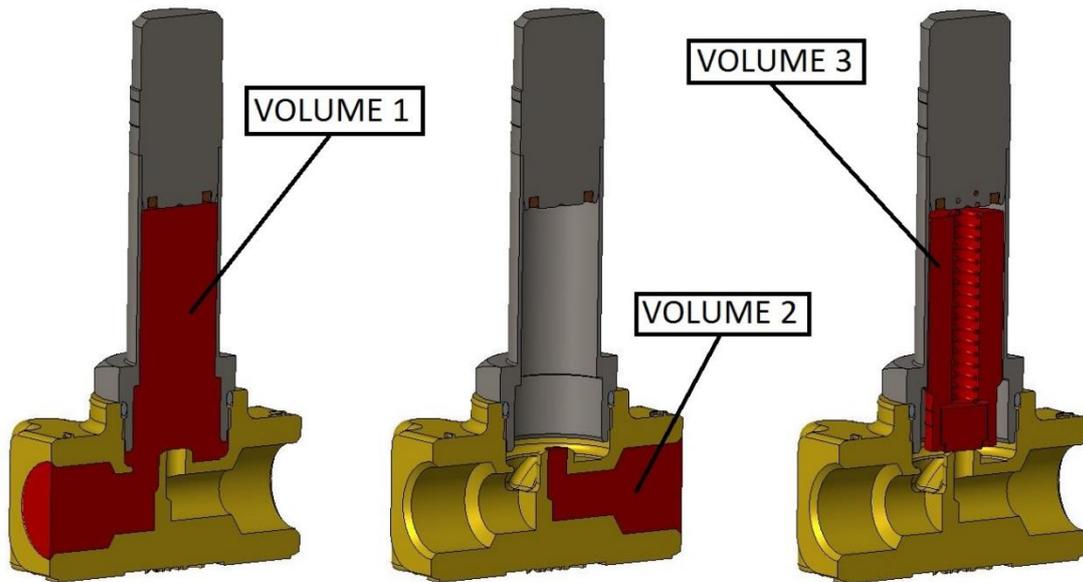


Figure 3-3: The three components used to calculate the inner volume of the valve

Figure 3-4 identifies the two components of the inner volume described above with different colors, volume A indicates the one upstream of the orifice while the volume B the downstream one.

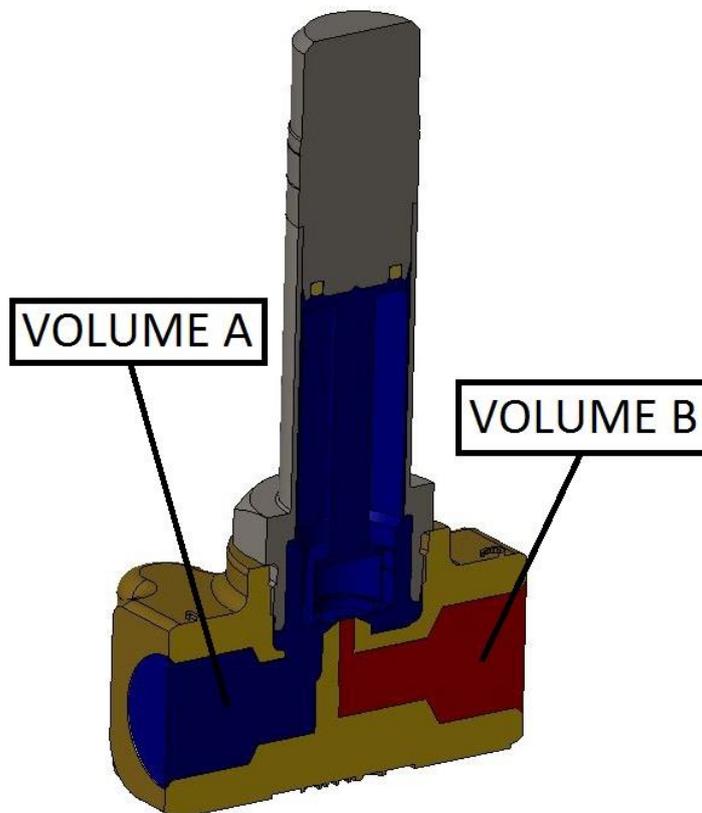


Figure 3-4: Inner free volume of a solenoid valve

The motivation for the division of the internal volume into these two components is due to the various types of testing that may be needed for a valve. In fact, a classic 2-way valve, as shown in the figures, is subjected to a single test with closed valve that only fills the volume upstream the orifice (Volume A), thus ensuring that all seals of interest are checked at the same time. If, instead, the same valve is transformed into a 3-way, maintaining the same body and changing the complete plunger and the fixed core, the test becomes made up of two different cycles, first filling the valve closed entering from the outlet pipe (Volume B) and the sealing of the shutter on the orifice is checked, after that the valve is opened and filled completely (Volume C given by the sum of A and B) so as to evaluate the welding, the mechanical seal between the body and the armature tube and the upper shutter-orifice joining. In this way, calculating for a valve volumes A and B, all the information needed for both the 2-way version and the 3-way version are known.

For the 89 codes obtained from the Pareto analysis, the volumes described above are then calculated, generating a table, of which only the first lines are reported as an example in Table 10.

ID	Valve code	V test A [cm ³]	V test B [cm ³]	V test C [cm ³]
1	JN1	1,372	0,579	1,951
2	A1	2,422	0,128	2,549
3	A2	3,788	1,493	5,280
4	A3	3,292	0,882	4,174
5	JP1	1,511	0,577	2,088
6	WA4	15,387	10,156	25,543
7	TG2	2,283	1,461	3,744
8	H8	12,009	6,879	18,888
9	5315	3,786	0,318	4,104
10	JPB	1,509	0,611	2,120
...

Table 10: First rows of the table that resume the inner volumes for the most important valves

For some codes, the issue of volumes is slightly more complex, in fact, ODE produces and sells, as well as single valves, the so-called manifold, i.e. products with a single body to which several solenoid valves are connected. For these elements, it is no

longer meaningful to speak of upstream or downstream of the orifice, so the volumes required for the specific tests for each manifold are directly calculated.

3.3 SORTING VALVES INTO FAMILIES

Now, having a fully populated table that contains all the volumes needed for the different types of tests, it is possible to generate the testing families. At each family will be assigned a test cycle with ad hoc parameters, the determination of which will be the next step of the project.

If all the codes of a family will be subjected to the same test, they must have a similar internal volume, provide the same filling pressure and have the same maximum acceptable loss. In addition, the choice is to keep divided the valves with different operating principle, which are characterized by a very different geometry. In particular, the valves with pilot control or combined operation solenoid valves, unlike the direct acting ones and manifolds, contain a diaphragm which, because of its elasticity, represents a destabilizing element when it is tested with the pressurized valve, and thus needs different timings.

Following what has just been said, the test cycles are initially divided according to the type of valve: automatic drink-dispensers, direct acting, manifold, with pilot control or combined operation and separating. In the first phase, the work will be focused to determining the parameters related to the direct acting, the manifold and the pilot control or combined operation, which are the most common types produced. Instead the valves with an operating principle different from those just mentioned are initially neglected.

Subsequently, each type is further subdivided according to the free volume inside the valve; finally, the last distinctions are made according to the filling pressure of the valve and the accepted leakage (in flow unit). To handle these distinctions within the test cycles, a special encoding is created as shown in Table 11.

LEAKAGE TEST CODING:					
N.bit	1	2	3	4	5
Letter/number	L	N	N	L	L
Meaning	Type of the valve	Progressive N. function of volume		Filling pressure	Test type / leakage accepted

Table 11: Coding for the leakage test cycles for the different solenoid valves

For this encoding each cycle is named with a 5-digit code with the following meaning: the first digit is a letter indicating the type of valve depending on the operating principle; the second and third digits are numbers related to the volume inside the valves for the cycle under examination; the fourth digit is a letter relative to a specific filling pressure and finally the last digit is again a letter representing the type of the test in terms of the accepted leakage flow.

Going more into the details, the tables below explain the meaning of all the values that each digit can have.

1	2/3	Volume range [cm ³]	
		MIN	MAX
D/G	05	0	0,5
	10	0,5	1
	15	1	1,5
	20	1,5	2,5
	25	2,5	3,5
	30	3,5	4,5
	35	4,5	6
	40	6	7,5
	45	7,5	9,5
	50	9,5	12
	55	12	15
	60	15	18,5
	65	18,5	22,5
	70	22,5	27,5
	75	27,5	33,5

1	Type of the valve
D	direct
G	manifold
S	combined oper.
S	pilot control

Table 12: Possible values of the first digit with the relative meaning

1	2/3	Volume range [cm ³]	
		MIN	MAX
S	05	0	5
	10	5	11
	15	11	18
	20	18	26,5
	25	26,5	37
	30	37	49,5
	35	49,5	64,5
	40	64,5	82,5
	45	82,5	104
	50	104	130
	55	130	161
	60	161	198
	65	198	242,5

Table 13: Possible values of the second and third digit with the indication of the volume range

4	Filling pressure [bar]
M	5
N	10
O	15
P	20

Table 14: Possible values of the fourth digit with the relative meaning

5	Test type
A	Classic (4 cc/h)
B	Sealing R/T
C	Sealing R/T 3a way
D	OR test

Table 15: Possible values of the fifth digit with the relative meaning

Generated in this way the cycles, each valve code needs to be associated with the corresponding cycle. Each valve can need a single test cycle or up to three different cycles, which means that there is no bi-directional relationship between the valve and the cycles. In fact, a valve can be associated with more than one cycle and vice versa each cycle can be related with different valve codes that have similar characteristics.

Shall be kept in mind that in the generation of cycles only the most important codes, from the point of view of the produced quantities, are taken into account. For this reason it is possible that the generated basic cycles do not cover all the different typologies of the valve and in those cases new cycles shall be created according to this procedure.

The result of this analysis is summarized in Table 16; here it can be seen the 46 cycles needed to cope with most of the solenoid valves produced. For each of these is also indicated the number of different codes associated and the amount of valves that, according to sales data of 2016, will be subjected to the test cycle in a year.

Test cycle	Count of associated valves	Sum of quantity of valves in 2016	Test cycle	Count of associated valves	Sum of quantity of valves in 2016
D05NA	1	7250	D35MA	13	3849
D05OA	23	105168	D35NB	5	5012
D05OB	17	127554	D35OA	47	36775
D10NA	1	6550	D40OA	1	3450
D10OA	67	183971	D45MA	13	6786
D10OB	7	13720	D50NA	1	13795
D15NA	39	334480	G15OA	3	10758
D15NB	1	3473	G20OA	11	19800
D15OA	31	44402	G25OA	23	28125
D15OB	7	6374	G30OA	21	69986
D20MA	7	12671	G35OA	13	14706
D20NA	56	175973	G40OA	11	41713
D20NB	25	22299	G45OA	5	26500
D20OA	52	117739	G50OA	4	10640
D25NA	46	86563	S10NA	11	31641
D25NB	13	12501	S15NA	77	124781
D25OA	32	185750	S20NA	31	42568
D30MA	44	46179	S20ND	36	61509
D30NA	69	136991	S30NA	34	23047
D30NB	29	30351	S35NA	44	28895
D30OA	39	116363	S65NA	17	3525
D30OC	2	9125			

Table 16: Resume of the test cycles needed for the most important valve codes

Now for each cycle the fundamental parameters (times and pressures) have to be evaluated, this will be the topic of the next chapter.

4 CALCULATION OF THE TEST CYCLE PARAMETERS

4.1 INTRODUCTION TO THE MAIN TEST CYCLE PARAMETERS

The test cycle carried out using the pressure decay ATEQ instrument has already been described in the second chapter. However, it is useful to recall the basic parameters of this cycle with a brief description:

- **Wait time** (or coupling time): in the case of manual tests, such as the solenoid valve tests performed in ODE, this parameter is not relevant and can be safely set to 0.
- **Fill Time**: time needed to fully fill the valve with air at a given pressure, it will be function of the valve volume and filling pressure you want to obtain. According to ATEQ indications, this can be obtained by following an experimental procedure: calculate a fill time overestimated with the formula $\sqrt[4]{V[cm^3] * p_{test}[mbar]}$, then with repeated attempts to go to lower this time as long as the situation remains stable (the drop in pressure read at the end of the test remains fairly constant), when a value completely disagrees with the previous detected ones, it means that the identified fill time is enough. At this point you just need to raise the time back to the previous value and you get the minimum time needed to completely fill the valve. We assume that the formula given by ATEQ implies a constant that allows to give a result in seconds as unit of measure.
- **Stabilization Time**: it evaluates the time required by the valve to reach a state of stability from the points of view of thermal effects, expansion of material and turbulence of the air entering in the valve, just after being pressurized. As the fill time, it will be function of volume and filling pressure, but also and above all of the structure (geometry and materials) of the valve. To obtain the value of this timing ATEQ still recommends the experimental procedure described above, using as the starting value $t_0 = 4 * t_{filling}$, where $t_{filling}$ is the value obtained with the first procedure.
- **Test Time**: time to assess the pressure drop, should be a fair compromise between the possibility to mediate the results over a sufficiently long period and the desire to increase productivity by minimizing the cycle times. Now, for most

of the cycles, a time of 4 s is used, value suggested by ATEQ itself. It is decided to keep the same value also for the new cycle created during this project.

- **Dump time:** once again, due to the manual nature of the test operation, this is not a real useful parameter and can therefore be set to 0.
- **Filling pressure:** parameter to be decided during the design of the test, it is important to underline how this will have an influence on both the timings and the pressure drop that can be accepted. At the moment the general rule is that the 2-way valves are tested at 10 bar if the diameter of the orifice is at most 3 mm, in the case of higher ones are tested at 5 bar, instead for the 3-way and for other particular solenoid valves, the test pressure follows what it is indicated on the label and on the test plan.
- **Accepted leakage (in terms of flow):** parameter to be decided during the design phase; as previously stated, this value in most of the cases is 4 cm³/h.
- **Accepted leakage (in terms of pressure drop):** central parameter of the leakage test with ATEQ since what the instrument measures is exactly the differential pressure across the test, this limit must be calculated according to those other parameters of the cycle, i.e. filling pressure, filled volume and accepted leakage flow.

All these parameters must be determined for each of the above generated cycles. Specifically, the times will be obtained by a statistical study of the described experimental procedure, filling pressure and permissible flow loss will be decided according to the indications of the current test cycle while the permissible pressure fall will be computed according to the other parameters following a law that has to be determined. The evaluation of this function, which combines pressure loss with volume, filling pressure and leakage flow, will be the topic discussed below.

4.2 RELATION PRESSURE DROP – LEAKAGE

The topic of this sub-chapter is to identify which is the relation that links the pressure drop with the leakage flow, considering also the other parameters like internal volume and filling pressure. The reason of the importance of this relation lies in the fact that, on one hand, the leakage test performed with the ATEQ instrument measures a decay of the pressure, on the other hand instead, ODE certifies all the solenoid valves with a maximum value of leakage expressed as volumetric flow rate.

As a starting point, for the relation between pressure drop and leakage flow it is taken the ideal equation that ATEQ mentions in the user manual:

$$\Delta p [Pa/s] = \frac{F [cm^3/min]}{0.0006 * V [cm^3]}$$

This equation is obtained applying the ideal gas law ($pV = nRT$) at the specific system of a volume filled with pressurized air that after a certain time present a drop in the inner pressure.

The volume V , with pressurized air inside, has a leakage flow in cm^3/s equal to F . Due to this leakage, after t seconds the moles of gas lost from the test volume are:

$$n_{lost} = \frac{F * t * p_{atm}}{R * T}$$

Where p_{atm} stand for the value of the atmospheric pressure; and so, the moles remaining in the volume are the difference between the ones at the beginning and the lost ones:

$$n' = n - n_{lost} = \frac{p * V}{R * T} - \frac{F * t * p_{atm}}{R * T}$$

Assuming a constant temperature, the pressure after time t is:

$$p' = \frac{n' * R * T}{V} = \frac{p * V}{R * T} - \frac{F * t * p_{atm}}{R * T} * R * T = p - \frac{F * t * p_{atm}}{V}$$

$$dp = p - p' = \frac{F * t * p_{atm}}{V}$$

$$\frac{dp}{t} = \frac{F * p_{atm}}{V}$$

With dp in [Pa], t in [s], F in [m^3/s], p_{atm} in [Pa] and V in [m^3]

Then, transforming the volume V in [cm^3], the flow F in [cm^3/min] and substituting at p_{atm} the approximated value of 10^5 Pa (to be more precise should be 101'325 Pa), we will obtain exactly the formula written in the ATEQ manual.

The relation says that, if a constant volume is considered, the pressure decay is directly proportional to the flow of leakage; instead between pressure drop and volume there is an inverse proportionality. These means that the same flow of leakage results in a

different pressure drop depending on the volume, in particular with a large volume we will see a small pressure decay instead with a smaller volume the decay will be larger.

4.2.1 Calibration with master leaks

The proposed relation has been verified with an experimental procedure. The first step for the calibration is the selection of three master leaks (Figure 4-1) that are present in the company. The master leak is a jet with an amount of flow that had been measured and certificated by ATEQ itself and that can be used to simulate a known leakage when connected to the pneumatic system of the ATEQ instrument. In particular these three master leaks have a flow equal to 4.5, 9.5 and 15.5 cm³/h with a filling pressure of 10 bar and they are provided with a push-in system to easily connect it with the instrument (Figure 4-2). The uncertainty of the master leaks is within $\pm 5\%$.



Figure 4-1: Master leaks (of 15.5, 9.5 and 4.5 cm³/h) with the relative certificates reporting the main information



Figure 4-2: Detail of the master leak of 15.5 cm³/h

The idea is to verify the relation between pressure drop and flow of leakage when the filling pressure and the volume are constant; the filling pressure was set to the value used in the calibration certificate. The volumes of the master leaks are the same because what changes is the dimension of hole that generates the nozzle. Actually, the leak is not made with a real hole because to reach so low flow the dimension should be very small and difficult to be made, so the desired flow is generated compressing a sort of filter to allow the passage of only a certain quantity of air. Moreover the volume of the master leaks is negligible with respect to the one of the entire system of measurement.

What is physically done is connecting the master leak to the ATEQ circuit in order to generate the certificated leakage flow. When the master leak is connected a test cycle is run and data are saved. The used test cycle has these parameters: filling time of 4 s, stabilization time of 7 s, test time of 10 s (in order to have a better average of the pressure decay value) and filling pressure of 10 bar. This procedure is repeated 7 times (to have a statistically reliable value) for each master leak and also 7 times without any master leak, only filling the pneumatic circuit, i.e. pipes and connections. From ideal point of view at this last case should correspond a flow of leakage equal to zero and so a null pressure drop; this will be used as zero value for the ATEQ instrument. It's

important to remark that between two different cycles at least 2 minutes of wait are needed to allow the system to return in equilibrium and avoid that the effect of repeated tests affects the results.

We are interested in the pressure drop in Pascal that the instrument measure for each master leak, this value divided by 10 (the duration of the test), gives the Pa/s of the decay related to the specific leakage flow. This relation, to be easily understood, is plotted on a XY graph, as shown in Figure 4-3, where on the horizontal axis there is the leakage flow instead on the vertical one there is the pressure drop.

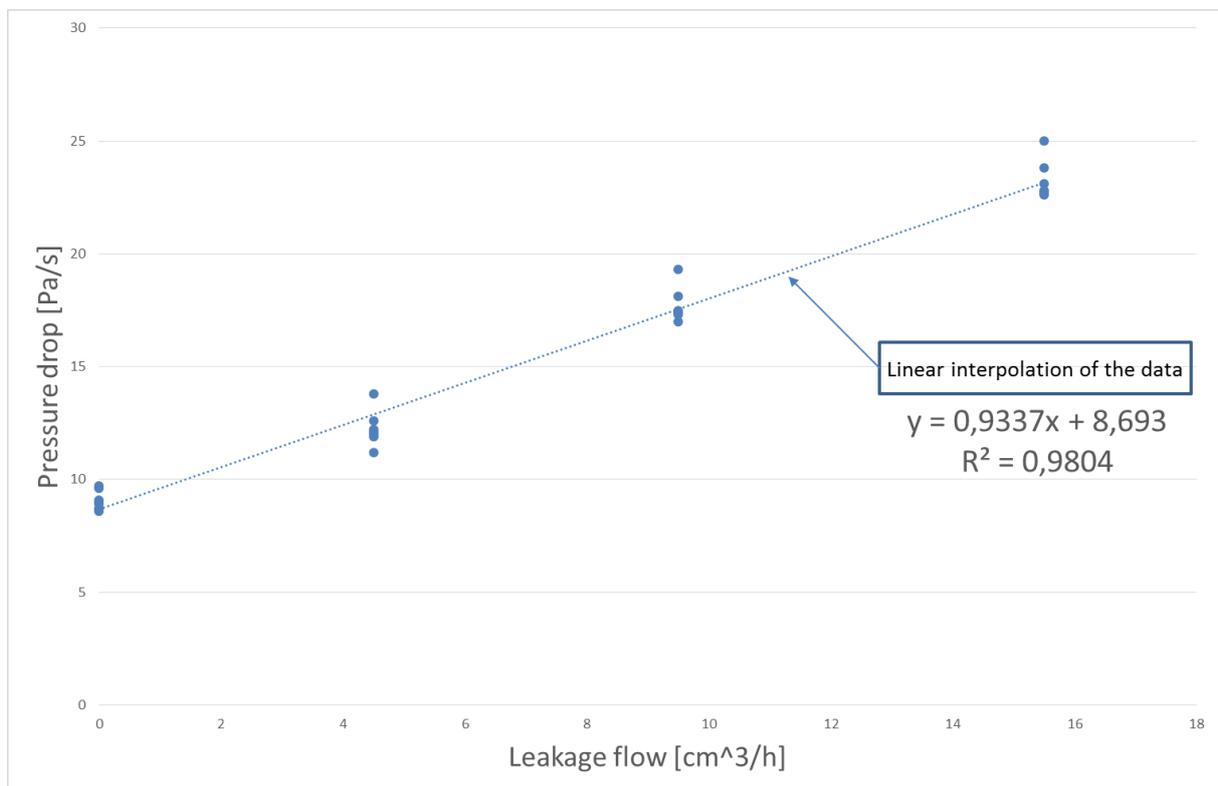


Figure 4-3: XY graph describing the relation between leakage flow and pressure drop

From the graph it can be seen that the data are grouped on four different vertical lines that correspond to the three master leaks and the situation with ideally no leak, than on each line the measurements show vertical spread due to the instrument variability. Now to find the relation “pressure drop – leakage flow”, an interpolation between the data is needed and it can be observed that a linear one is fitting the measured points. With the use of Excel it’s possible to calculate uncertainty related to linearity; these information are reported in Table 17 below.

m:	0,934	8,693	: q
errSt_m:	0,025	0,234	: errSt_q
R^2:	98%	0,797	: stl_OUT

Table 17: Linear regression statistics

In the first row are reported the characteristic parameters of the line, slope and y-intercept that were also reported in the graph. In the second row, instead, there are their standard errors, respectively of the slope and of the intercept, that in this case are a bit lower than the 3% of the nominal value. Finally the last row gives the value of R^2 , coefficient of determination, and the standard deviation of linearity. The value of R^2 very close to 1 is a confirmation of the goodness of the linear model. Instead the standard deviation of linearity gives the value of the uncertainty for the output, the pressure drop, and so it is expressed in Pa/s. If we divide this value by the sensibility, that is the slope of the line, we can obtain also the uncertainty of the input, i.e. the leakage flow rate in cm^3/h . In this case the uncertainty is equal to $0.85 \text{ cm}^3/\text{h}$ that compared with the typical value of the limit flow rate $4 \text{ cm}^3/\text{h}$, gives a worst case uncertainty of 29% on the limit value of the flow rate, considering both the uncertainty of measurement of the ATEQ instrument and the intrinsic uncertainty of the value of flow of the master leak.

A thing to notice of the model is the value of pressure drop associated with a leakage flow equal to 0, correspondent to the intercept of the regression line, which is different from zero. Moreover, we can observe that the value of this y-intercept (9 Pa/s) is very important if compared with the overall pressure drop associated with a typical flow of $4 \text{ cm}^3/\text{h}$ (13 Pa/s).

From a theoretical point of view this is impossible because no leakage should result in no pressure drop; this is also in accordance with the ideal formula written before: $\Delta p = \frac{F}{0.0006 \cdot V}$ where the line should go through the origin of the axes. But in this analysis, leakage flow equal to 0 means that only the circuit is filled with pressurized air, no master leak added, but, as can be expected, the circuit has intrinsic sources of leakage at the connections or due to the fact that the elastic material of the pipes is subjected to deformations that creates a variation on the filled volume, seen from the instrument as a pressure decay. This should be taken into account also when the real leakage test will be performed because a part of the pressure drop measured by the ATEQ

instrument is due to this intrinsic leakage of the system and so it is not related to a leakage of the solenoid valve.

To better understand this phenomenon of the so called “leakage of zero” a further data collection is performed. The same basic cycle as before is executed on the simple measuring circuit, with nothing connected at the end, to evaluate the entity of the leakage associated only to the circuit and so intrinsic in each cycle performed. The cycle is performed with different filling pressures that cover the typical range of pressure used during the testing phase in the company (5, 7.5, 10, 12.5 and 15 bar), repeating the test six times at each point. The obtained results in terms of pressure drop (Pa/s) are plotted in a graph with the filling pressure on the x-axis, as shown in Figure 4-4.

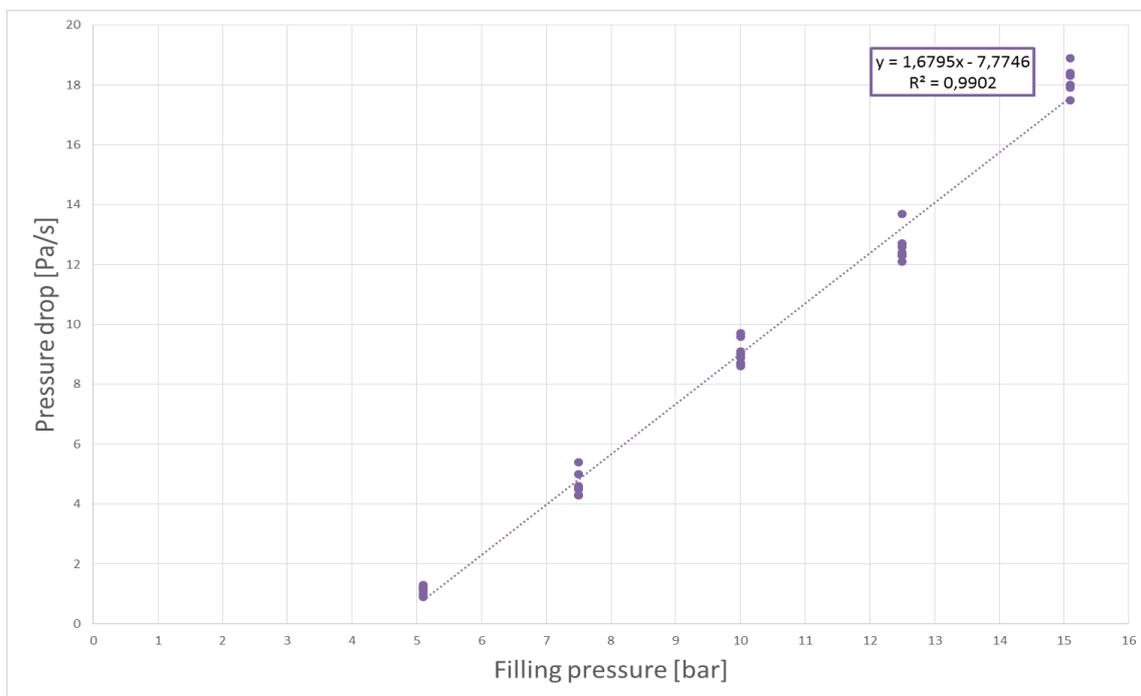


Figure 4-4: XY graph that represent the “leakage of zero” in function of the filling pressure

The graph shows that with the increase of the filling pressure also the pressure drop clearly increases with a trend almost linear. This means that with high filling pressure the intrinsic leakage associated with the measuring circuit is very important, up to 18 Pa/s, instead at low pressure the intrinsic leakage becomes less important. This leakage should be considered also in the next step during the setting up of the parameter of the cycles because now we know that the pressure drop measured is no more due only to the valve’s leakages but also to the circuit ones. Moreover, if “zero” leakage is present, this value should be used to correct the true leakage on the

solenoid valve; this correction is important because acts directly on the acceptance or rejection of the tested valve.

4.2.2 Calibration with flowmeter

Experimental activity has been performed on the ATEQ instrument using a flowmeter (represented in Figure 4-5), provided by ATEQ, made with a pipe and a mechanical valve for the regulation of the concentrated leakage flow (Figure 4-6). This instrument allows to overcome the main problem related to the usage of the master leaks that are bonded to one filling pressure, i.e. 10 bar. In order to study the relation pressure drop – leakage flow changing the filling pressure the flowmeter is used. This flowmeter, called ATEQ CDF, has the following characteristics: a measuring range from 0.06 to 120 cm³/h, an accuracy of 0.6 cm³/h + 2% of the reading value and a resolution of 0.06 cm³/h. Immediately from this data we can observed that the instrument has not the best characteristic for the aim of the project because we are focused on values of flow of few units instead the instrument covers a huge range of measure consequently with a lost in terms of accuracy. In this way we know that calibrating tool introduces an uncertainty around 20% if the limit flow rate is measured (i.e. 4 cm³/h); added uncertainty cannot be neglected and has to be added to the one of the calibrated instrument. Nevertheless the choice is to use this instrument because it was already present in the company and furthermore, also after a research of alternative instruments, it was found that it represents a good trade off for measuring low flows of gasses and costs.



Figure 4-5: ATEQ flowmeter for the calibration of the leakage flow



Figure 4-6: ATEQ flowmeter connected with the regulation valve and pipe through a push-in system

The use of the flowmeter gives the possibility to relate the flow of the leakage with the pressure decay measured by the ATEQ instrument and study their relation, also in function of the other parameters like volume and filling pressure.

In order to do the calibration, what is actually done is to connect the flowmeter, using the pipe, to the pressure decay leak measuring instrument; in particular the instrument has a connection port on the front side so that the pipe can easily be connected using a push-in system. In this way the pipe, the valve and the flowmeter are connected to the pneumatic circuit of the ATEQ instrument and they can be filled with pressurized air when a cycle starts. Regulating the valve it is possible to create a variable leak, whose value can be assessed reading the value on the flowmeter.

As already done with the master leak, also in this case a number of points relating different leak flows with the relative pressure decays are collected in order to find the existing relation between the two quantities. The great advantage of this second calibration method is that the data collection can be done at different filling pressures

because the value of the leakage flow can be read in real time; indeed the master leaks are valid only for the pressure declared in the calibration datasheet.

300 points were collected, divided in ten different acquisitions of 30 points each. The ten different acquisitions are equally distributed on five filling pressure (5, 7.5, 10, 12.5 and 15 bar) so to finally have for each pressure 60 points distributed over a range of flow from 4 to 17 cm³/h more or less. The basic cycle used for each acquisition is characterized by filling time of 7 s, stabilization time of 11 s and test time of 15 in order to have a better average. The filling pressure, instead, is the one that has to be studied and the pressure drop limit is set to 0 because in this phase we are not interested in the acceptability of the test.

From a theoretical point of view, according to the formula $\Delta p [Pa/s] = \frac{F [cm^3/min]}{0.0006 * V [cm^3]}$ already described, the filling pressure should not have an influence on the pressure decay. Considering that the volume filled with the air is maintained constant during all the data collection period, the linear relation between Δp and F means that all those 300 points collected should be distributed along a line in a X-Y graph with the leakage flow on the horizontal axis and the pressure decay on the vertical axis. The Figure 4-7 report exactly this kind of graph in which all the points are reported, indicating with different colors the points derived from different filling pressure.

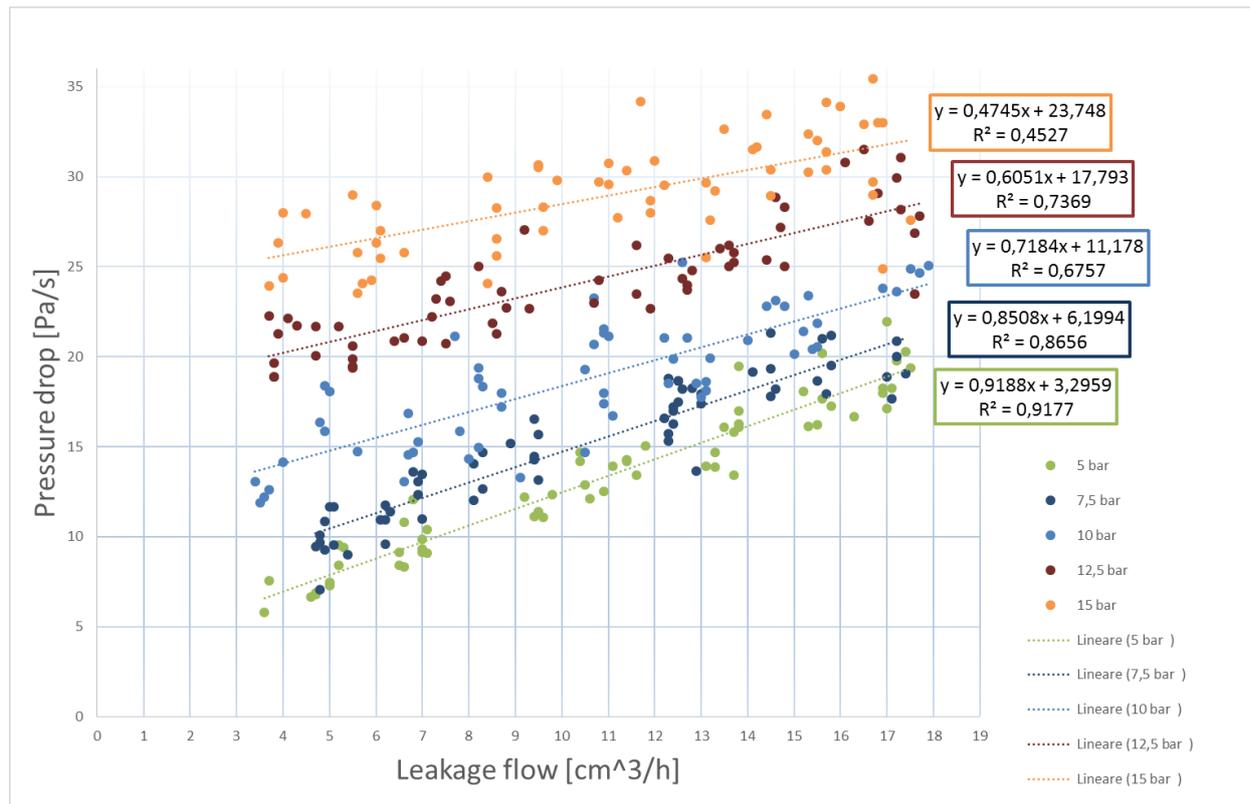


Figure 4-7: XY graph describing the relation between leakage flow and pressure drop at different filling pressure built using the flowmeter

Looking at the graph it can be immediately seen that the data are definitely not grouped along a single line as expected. On the contrary they can be collected in five different lines, one for each filling pressure; this interpolation lines are sketched with dotted lines and their main parameters are reported in the boxes on the right. Furthermore, as it was already for the master leaks, the value of each correlation line corresponding to a null leakage flow is different from zero. As for the master leak, the reason is due to the fact that zero leakage flow means regulating valve completely closed but the intrinsic sources of leakage of the system are still present and so a pressure decay will be seen. Furthermore, the intrinsic source of leakage of the system is for sure strictly connected with the system itself; for this reason if we compare the y-intercept of the line at 10 bar with the one founded with master leaks we immediately notice a difference. In particular the value with the flowmeter is higher than the previous one, this is due to the addition at the system of a further element that is the tube with the regulating valve, bringing to an increase of the measured intrinsic leakage.

The intrinsic leakage can be considered, in some way, also the reason of the big difference between the lines of the five different pressures. Indeed the simple system

circuit has some causes of leakage that are always the same from a geometrical point of view. But as demonstrated in the previous subchapter, filling the circuit with different pressures brings to different intrinsic pressure drops that is the reason why the five lines are shifted vertically one from the other. We can overcome this issue subtracting at each data the value of the own y-intercept, obtaining the situation depicted in Figure 4-8. With this analysis we can notice that the filling pressure has an impact in some way also on the slope of the calibration lines.

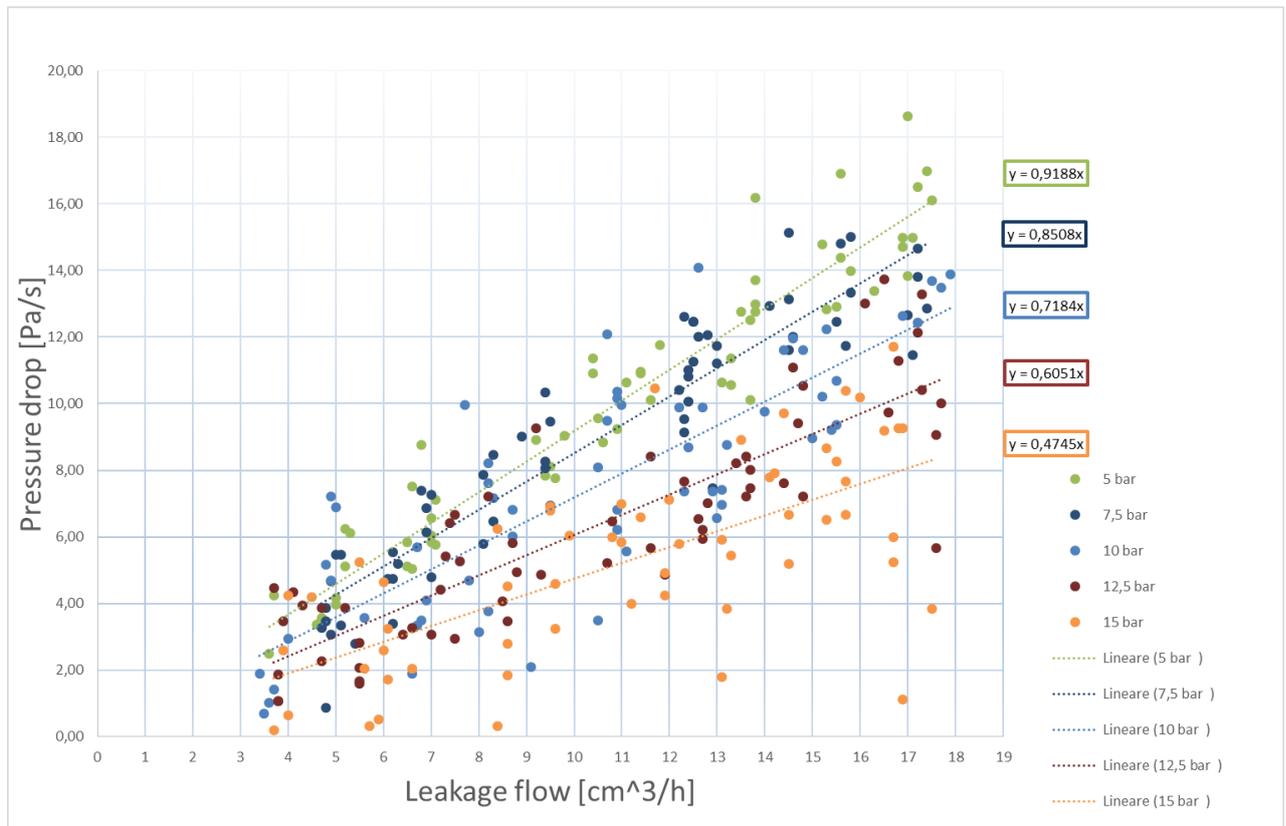


Figure 4-8: XY graph describing the relation between leakage flow and pressure drop at different filling pressure with data shifted of the value of y-intercept

As we did with the master leak's analysis, it is possible to calculate the additional information of all the five linear regressions reported in the graph, one for each filling pressure. These statistics are collected in the tables below.

5 bar			
m:	0,919	3,296	: q
errSt_m:	0,036	0,424	: errSt_q
R^2:	92%	1,201	: stl_OUT
		1,3077	: stl_IN

7,5 bar			
m:	0,851	6,199	: q
errSt_m:	0,044	0,495	: errSt_q
R^2:	87%	1,387	: stl_OUT
		1,6306	: stl_IN

10 bar			
m:	0,718	11,178	: q
errSt_m:	0,065	0,739	: errSt_q
R^2:	68%	2,069	: stl_OUT
		2,8806	: stl_IN

12,5 bar			
m:	0,605	17,793	: q
errSt_m:	0,047	0,536	: errSt_q
R^2:	74%	1,657	: stl_OUT
		2,7379	: stl_IN

15 bar			
m:	0,474	23,748	: q
errSt_m:	0,069	0,814	: errSt_q
R^2:	45%	2,221	: stl_OUT
		4,6811	: stl_IN

Table 18: Tables collecting the additional parameters of the regression lines for the data collected with the use of the flowmeter at different filling pressure

Recalling the meaning of the data: “m” is the slope of the line, “q” is the y-intercept, “errSt_m” and “errSt_q” are the standard errors of the slope and intercept, “R²” is the coefficient of determination, “stl_OUT” is the standard deviation of linearity referred to the output quantity (pressure drop in [Pa/s]) and “stl_IN” is the one referred to the input (leakage flow [cm³/h]). The standard deviation of linearity gives the value of the uncertainty of the measure and we can see that these uncertainties have higher values with respect to the ones obtained during the analysis with the master leaks. This is the main drawback of the second analysis and it is mainly due to nature of the reference instrument used. In the first characterization, we used the master leaks that gives an uncertainty on the flow measure that is considerably lower than the correspondent with the ATEQ CDF.

It was decided to increase the number of samples, trying in this way to improve the accuracy of the evaluation. Each sample requires around 5 minutes to be acquired, considering the cycle time and the wait between two consecutive tests. Therefore a considerable increment of data for all the pressure will result in an activity very time consuming. So the choice is to focus the attention on the filling pressure of 10 bar that is the most common one.

In this specific condition other four acquisitions are performed and added to the previous two, reaching a sample composed by 180 points. These are plotted again on the X-Y graph, as reported in Figure 4-9.

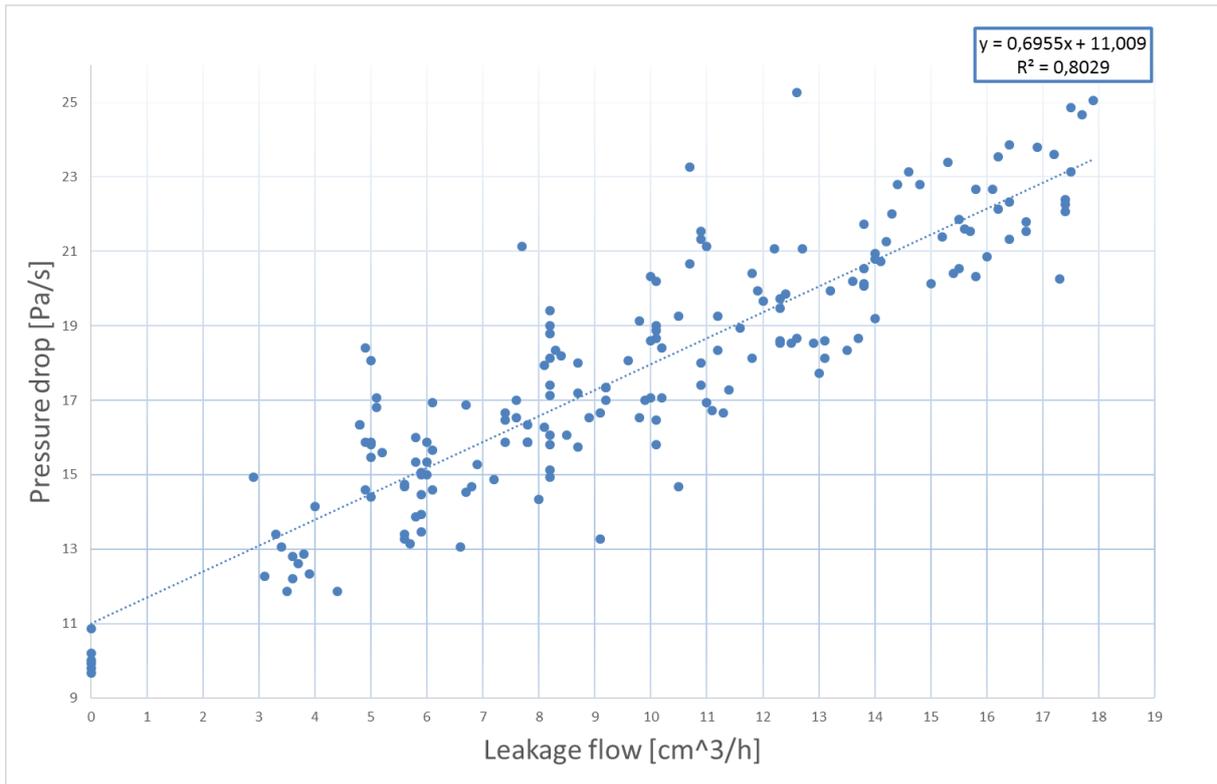


Figure 4-9: XY graph describing the relation between leakage flow and pressure drop at 10 bar of filling pressure built using the flowmeter

The new situation for the relation leakage flow – pressure drop with 10 bar of filling pressure results more populated. For these 180 data the residue with respect to the regression line are calculated and plotted in Figure 4-10.

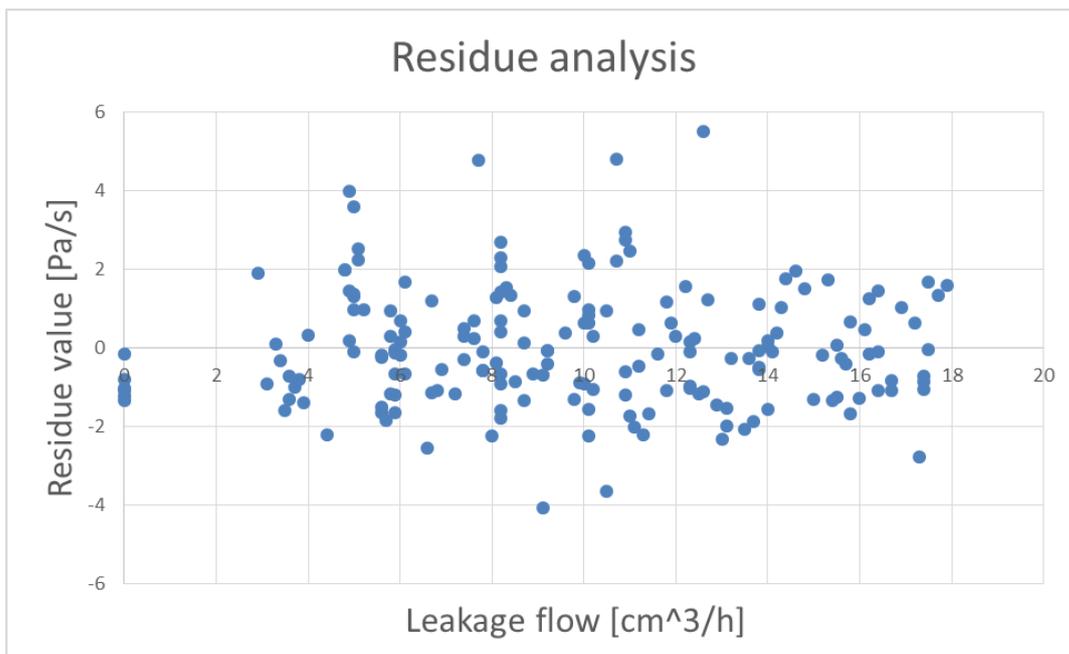


Figure 4-10: Residue analysis of the 180 data collected with filling pressure of 10 bar

The random distribution of these residuals is a confirmation that a linear trend is correct because the presence of both positive and negative residuals means that the data are equally distributed above and below the regression line.

Again the additional information of the regression line are calculated and presented in Table 19.

m:	0,69551	11,00866414	: q
errSt_m:	0,0254	0,271091607	: errSt_q
R^2:	0,8029	1,508845932	: stl_OUT
		2,169424865	: stl_IN

Table 19: Additional information of the regression line

Focusing the attention on the uncertainty values (of input and output), we can observe that the increase of the number of data brings a benefit in terms of uncertainty. The standard deviation of linearity of the output goes from a value of 2,1 to 1,5 Pa/s instead the one of the input from 2,9 to 2,2 cm³/h. Despite this, the uncertainties are still higher than the ones from the master leak's analysis, so the results from the first analysis provides better estimation of the measurement uncertainty.

Till now, only the influence of the filling pressure is considered in the relation pressure drop – leakage flow, instead the influence of the volume is not considered from experimental point of view because for each of the two calibrations it is used always the same volume. Furthermore used volumes are unknown, because the volume of the pneumatic circuit that is contained in the instrument cannot be calculated unlike the external pipe that can be measured. For this reason a further step is performed, where the filled volume is changed so to verify the theoretical approach and at the same time to calculate the internal volume of the instrument.

A data collection completely similar to the previous ones, with the same devices but with a different configuration is executed; to better understand the two different configurations, the figures below represents both the testing setups.

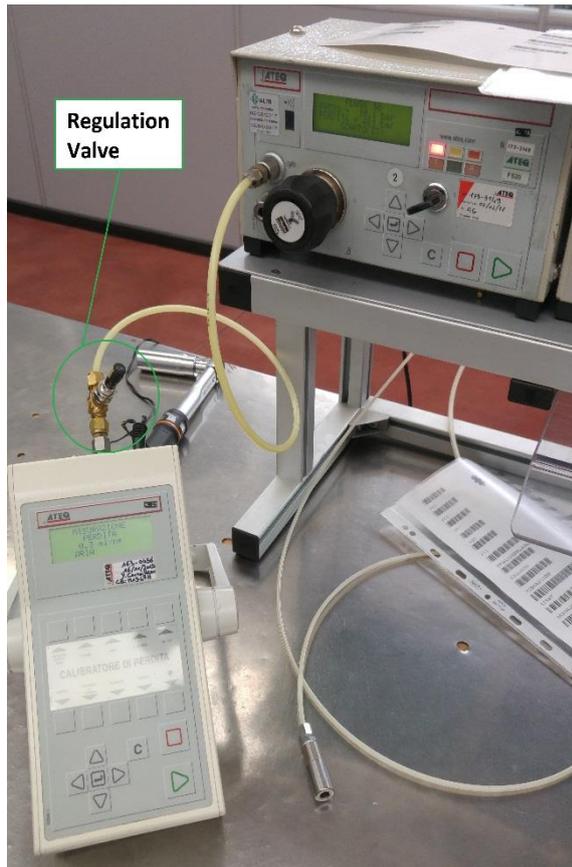


Figure 4-11: Configuration A: valve on the side of the flowmeter, volume higher

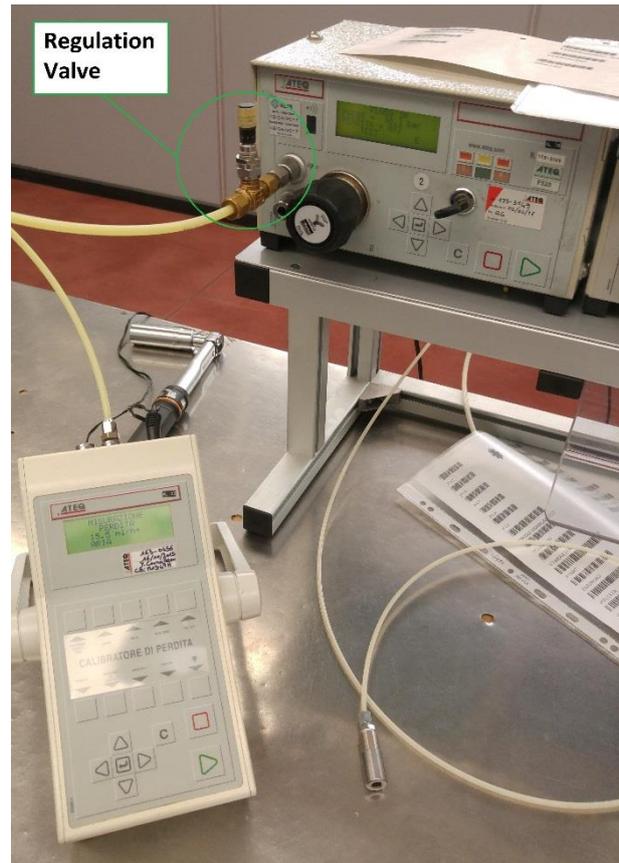


Figure 4-12: Configuration B: valve on the side of the instrument, volume smaller

The difference between the two configurations stands in the orientation of the pipe that connects the pressure decay measuring instrument with the flowmeter. In the first case the regulating valve is placed just before the flowmeter and so, when the cycle starts, all the pipe is filled with pressurized air. In the second case instead the tube is mounted on the outlet of the ATEQ instrument.

The further data collection with the new configuration is composed by four different acquisitions of 24 points each one, for a total of 96 points characterized by a certain flow of leakage and pressure drop, all with a filling pressure of 10 bar. These data are plotted in the X-Y graph with on the axes leakage flow VS pressure drop, obtaining what is represented in Figure 4-13.

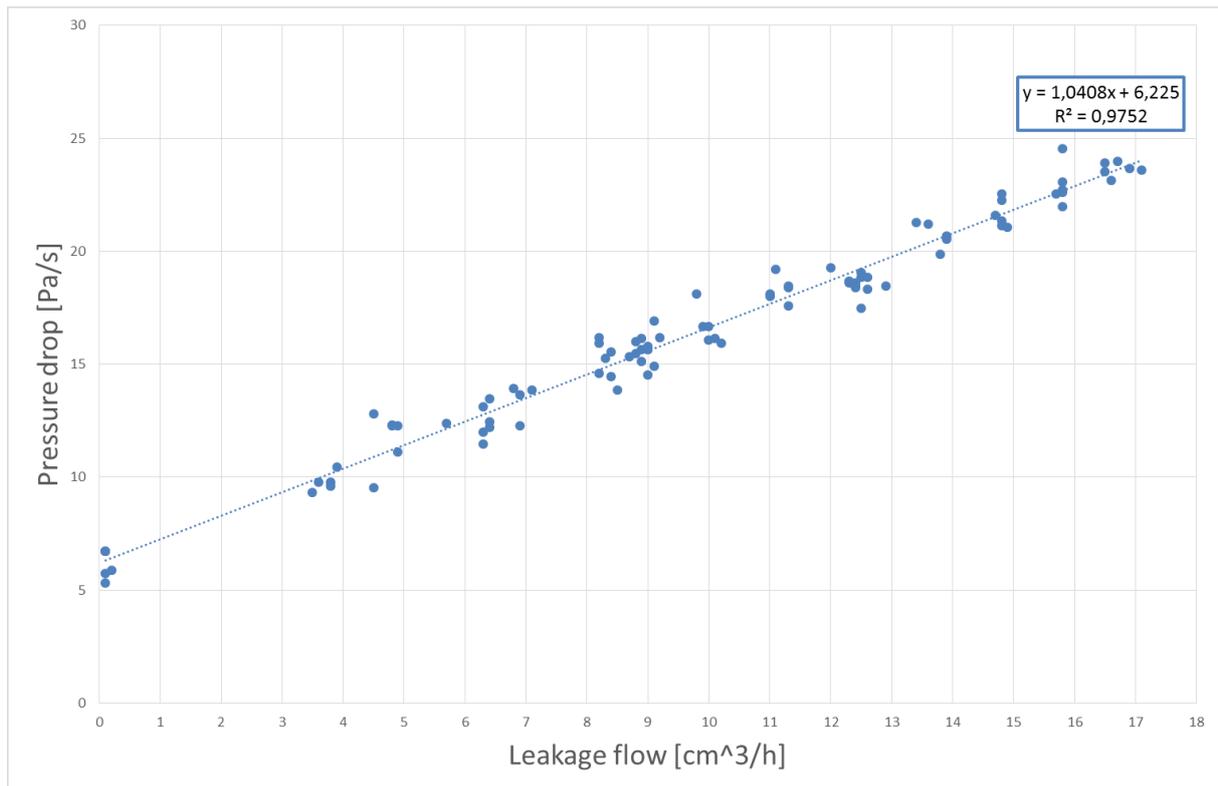


Figure 4-13: XY graph describing the relation between leakage flow and pressure drop at 10 bar of filling pressure built using the configuration B with the flowmeter

The study of the residue analysis in Figure 4-14 and of the additional parameters of the regression line in Table 20 gives further information on the linear correlation plotted in the graph. This model can be considered already precise with these 96 points due to the random distribution of the residues, R^2 very close to 1 and values of uncertainty acceptable.

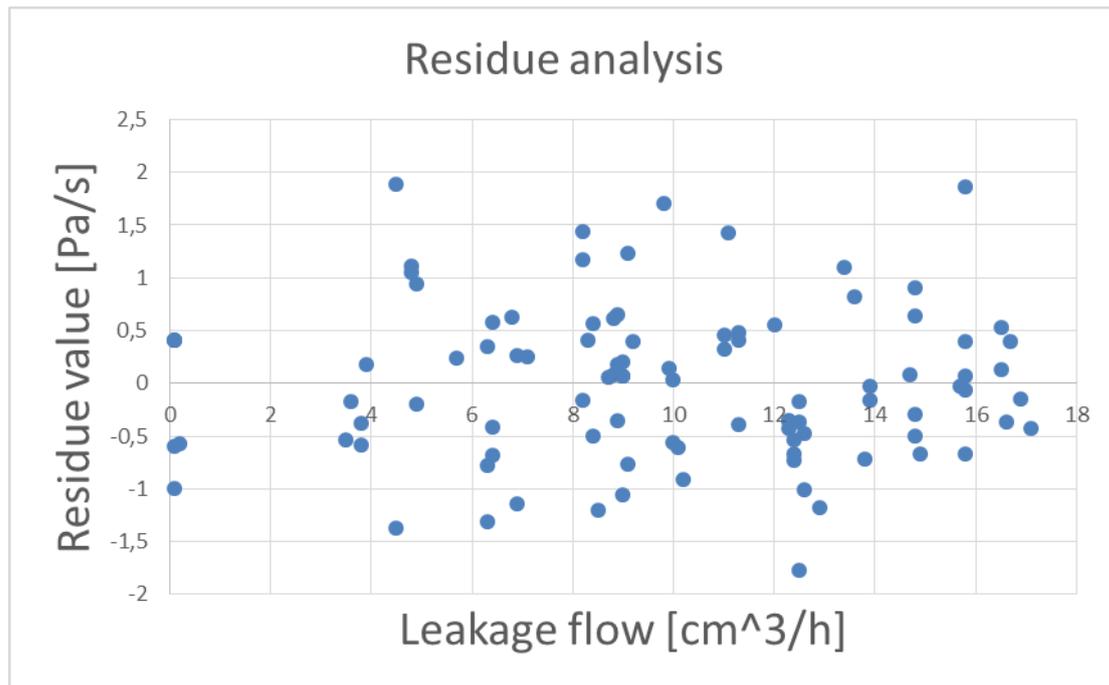


Figure 4-14: Residue analysis of the 96 data collected with flowmeter in configuration B

m:	1,040751	6,22502	: q
errSt_m:	0,017106	0,182982	: errSt_q
R^2:	0,975234	0,741654	: stl_OUT
		0,712615	: stl_IN

Table 20: Additional information of the regression line

Overlapping on the same graph this situation (configuration B), the previous one (configuration A) and also the one with the master leaks we obtain a graph like the one represented in Figure 4-15.

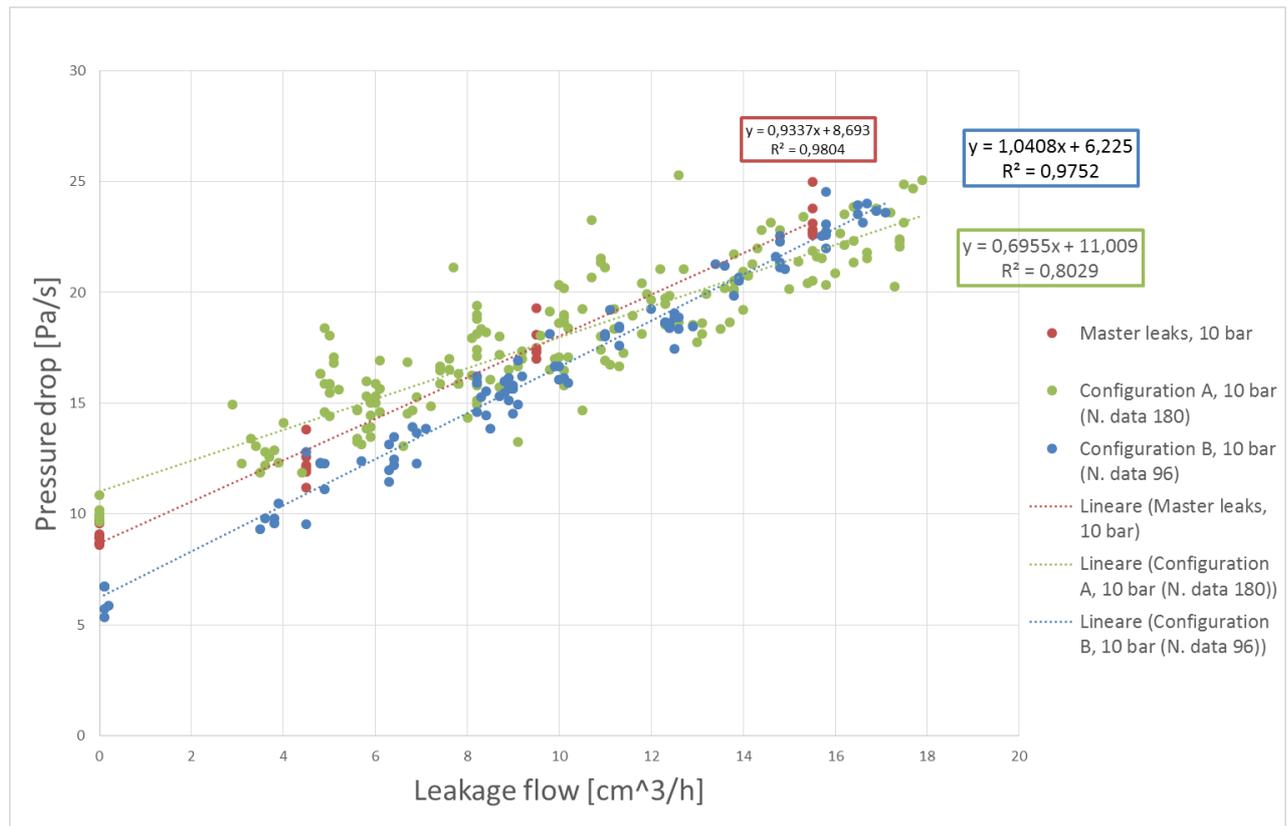


Figure 4-15: Comparison between the data with mater leaks and with flowmeter in the two configurations

If we compare the two configurations with the flowmeter, the line plotted in green represent the relation between leakage flow and pressure drop with the configuration A instead the blue line represent the configuration B and so the filling of a smaller volume. Neglecting the value of the y-intercept and focusing the attention on the slopes of the line we can notice that decreasing the volume the value of the slope increases. Recalling the theoretical formula that was already introduced

$$\Delta p [Pa/s] = \frac{F [cm^3/min]}{0.0006 * V [cm^3]} = \frac{F [cm^3/h]}{0.036 * V [cm^3]}$$

Indeed considering Δp as the dependent coordinate (y) and F as the independent coordinate (x) of the equation, the formula can be rewritten as $\Delta p = m * F$ where

$$m = f(V) = \frac{1}{0,036 * V}$$

Moreover comparing the curves obtained with master leaks and flowmeter in the same configuration (i.e. pressure) it can be noticed that the configuration B is very similar to the one with master leaks, especially regarding the slope of the line.

The measurement uncertainty in terms of linearity is similar with the two methods.

The fact that the term of the volume is placed in the denominator means that there is an inverse correlation between m and V , i.e. that an increase of one parameter brings to a decrease of the other and vice versa. This is exactly what we observed from the last graph.

Now it is possible to look also at the exact value of the two different slopes with flowmeter and not only at their trend; using the formula written above the value of the volume can be obtained from the slope as: $V = \frac{1}{0,036*m}$.

Substituting the values of m in the two configurations we obtain:

$$V_A = 39.939 \text{ cm}^3 \text{ and } V_B = 26.690 \text{ cm}^3$$

The difference between the two configurations, as we saw before, stands in the orientation of the pipe with attached the regulation valve. So the real difference in volume can be obtained measuring the geometric parameters of this pipe; then a comparison with the experimental difference can be done.

The pipe has an internal diameter equal to 4 mm and a length almost equal to 90 cm, using these information we can obtain the volume as: $\Delta V_{real} = \frac{d^2}{4} * \pi * L_0 = 11.3 \text{ cm}^3$

Instead the difference in terms of volumes calculated experimentally is equal to: $\Delta V_{exper} = V_A - V_B = 13.2 \text{ cm}^3$.

We can say that the two values are quite close (15% of difference) and so the theoretical approach has been qualitatively verified.

Furthermore the value of volume B can be used to calculate the volume of the system that is always present in all the test and so that has to be added to the one of the filled valve. This constant volume of the system is equal to the volume B minus the volume of the regulating valve that is the only addition in terms of volume done in configuration B. This value can be estimated to be almost equal to 1 cm^3 and so the volume of interest of the system is around 25.5 cm^3 .

4.2.3 Summary of the calibration pressure drop – leakage flow

At the end of the experimental phase, some conclusions can be drawn:

- There is a linear relation between the leakage flow and the pressure drop maintaining all the other parameters constant (volume and filling pressure); this is in accordance with the theoretical formula $\Delta p [Pa/s] = \frac{F [cm^3/min]}{0.0006 * V [cm^3]}$.
- The filling pressure has a not negligible effect in what is the leakage of the system, this quantity adds up to the one of the tested valves and so has to be considered when evaluating the performance of the tested valves;
- The influence of the volume is compliant to the indication of the theoretical formula, moreover experimental activity allowed indirect computation of the inner volume of the testing circuit that has to be added to the volume of the product to obtain the overall volume filled with pressurized air;
- The valve testing with the measurement chain used in the company, provides measurement uncertainties very high (ranging between 20 and 50 % of the limit value); the reason of these results lies in the accuracy of the used instruments.

Considering all these conclusions, the idea for the calculation of the accepted pressure drop starting from the value of the maximum leakage flow is to use the theoretical formula with an addition of a coefficient that is function of the filling pressure. This coefficient will reflect the y-intercept of the experimental lines and it has the meaning of considering the intrinsic leakage of the system, which is more critical the higher the filling pressure. To quantify this coefficient it can be recalled the study performed after the calibration with master leaks, in particular the equation of the line interpolating the data of pressure drop obtained filling only the measuring system. This equation, reported in Figure 4-4, allows to calculate the pressure drop (y) in function of the filling pressure (x) using the constant coefficients coming from the experimental analysis.

$$y = 1,6795 * x - 7,7746$$

$$\Delta p_0 [Pa/s] = f(p_{fill}) = 1,6795 * p_{fill} [bar] - 7,7746 = q_0$$

$$(with 5 < p_{fill} < 15 \text{ bar})$$

Instead the slope of the line, according to the theoretical formula, is function of the volume.

$$\Delta p_1 [Pa/s] = \frac{1}{0,036 * V [cm^3]} * F [cm^3/h]$$

$$m = f(V) = \frac{1}{0,036 * V}$$

Merging these two information, one for the y-intercept and the other for the slope, it is possible to create a single equation that links the pressure drop and the leakage flow:

$$\Delta p[\text{Pa/s}] = \frac{1}{0,036 * V[\text{cm}^3]} * F[\text{cm}^3/\text{h}] + 1,6795 * p_{fill}[\text{bar}] - 7,7746$$

In red in the formula we have the parameters that we want to link together so to have the possibility to pass from one to the other and vice versa, instead in blue there are the parameters of the system that affects this relation.

In this way, knowing the characteristics of the leakage test (so the filling pressure and the accepted leakage flow) and the characteristic of the valve (so the volume, that is the one of the valve variable in each test plus the one of the system that is always constant), it is possible to calculate the accepted pressure drop to set in the ATEQ instrument as the limit of the leakage test. If this approach is used, the measurement uncertainty of the pressure drops becomes ± 0.95 Pa/s, combining both the contribution of the linearity and the intercept varying the filling pressure.

4.3 STUDY OF THE CYCLE TIMES

The objective of this sub-chapter is to calculate the right values of the filling and the stabilization times. These two values are function of the volume filled and the filling pressure. Anyway there is not a formula that allows to calculate the time needed starting from the volume and pressure, there are just two formulas (one for filling time and the other for the stabilization time) provided by ATEQ, that represent the starting point for a further experimental estimation. According to the ATEQ manual, the starting value of the filling time for the experimental phase is $t_{fill,0} = \sqrt[4]{V[\text{cm}^3] * p_{fill}[\text{mbar}]}$ instead for the stabilization is $t_{stab,0} = 4 * t_{fill}$. These values represent the maximum limits of the times, then with the experimental phase we start to decrease step by step the value as long as a stable situation is guarantee. When the situation starts to be unstable, which means that two tests completely equivalent on the same valve give two completely different results, we can infer that the time is not sufficient to complete the process (filling or stabilizing) and so this represent the lower limit. The described

process is not performed on a single valve but on a sample composed by several valves of the same type in order to have a statistical validity of the results.

Due to the fact that the times are function of volume and filling pressure, it is quite clear that they would be different for most of the different basic cycles just created. Furthermore it is reasonable to think that also the inner geometry of the valve has an influence on the phenomena of filling and stabilization, so it is important to distinguish the valves with different operating principles; in particular the presence of an elastic element as the diaphragm represents a source of instability.

So what it is done is to take for each cycle N samples of a valve code relative to the specific cycle and through the experimental procedure obtain the optimum filling and stabilization times. In particular the procedure used is to start from a cycle with the filling and stabilization time derived from the formulas reported above, a test time of 4 s and as filling pressure the one proper of the specific cycle; it is important to underline that in this phase the limit of the pressure decay is not important because we are not interested in the absolute values of the pressure drops but in the trend of these values changing the times. With this cycle all the same valves, typically 10, are tested and an average value of pressure drop is obtained. Then the filling time is decreased of 2 s and the N tests are performed again obtaining another value of pressure drop; this step is repeated several times and all the values of pressure drop are plotted on a graph representing pressure drop vs filling time as reported in Figure 4-16 for the single values of the different valves and in Figure 4-17 as a mean of the 10 values. Sometimes it is possible to have a time step of 1 s in order to have a better resolution in particular areas of interest of the line describing the trend.

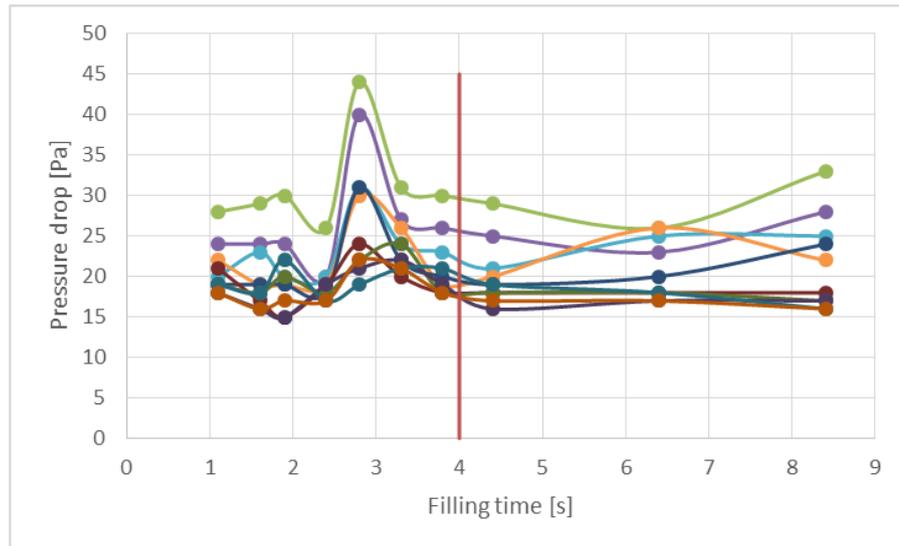


Figure 4-16: Graph representing the trend of the pressure drop as a function of the filling time for the 10 different valves

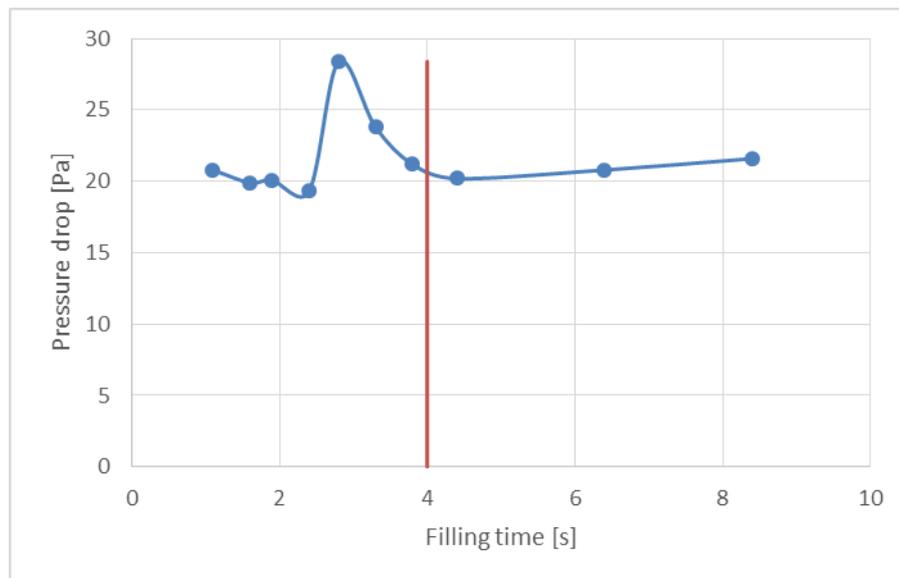


Figure 4-17: Graph representing the trend of the mean pressure drop as a function of the filling time

From the graph it is possible to find the value of the filling time under which the pressure drop start to increase suddenly and this is the critical value of the filling time to use in the cycle; in the reported example the value is marked with the red line and it is equal to 4 s.

Now, set the right value of the filling time, the same procedure is repeated varying the stabilization time. After the first tests it has been seen that the value derived from the theoretical formula is strongly overestimated, so the starting value for the further tests is set equal to the half of the nominal one. Two graphs similar to the previous ones are

created where on the x-axis there is the stabilization time instead of the filling time, like in Figure 4-18 and Figure 4-19.

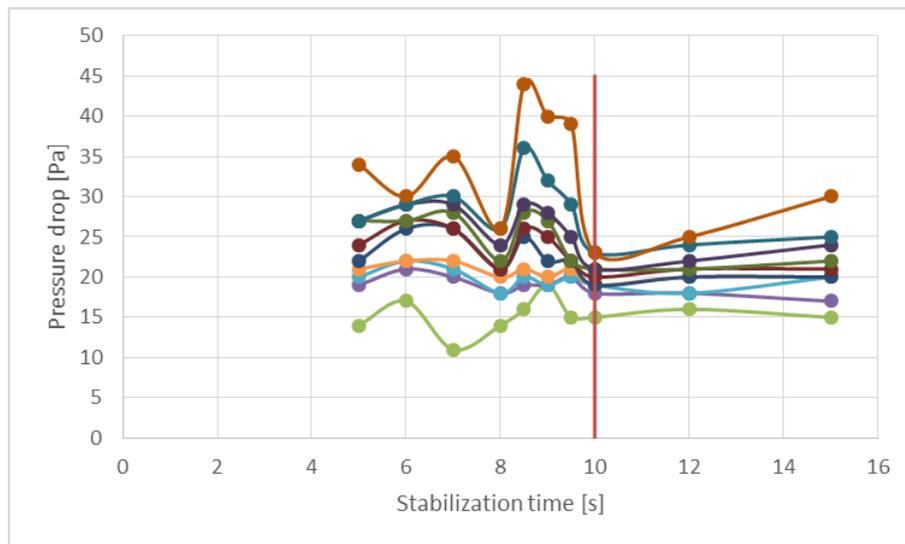


Figure 4-18: Graph representing the trend of the pressure drop as a function of the stabilization time for the 10 different valves

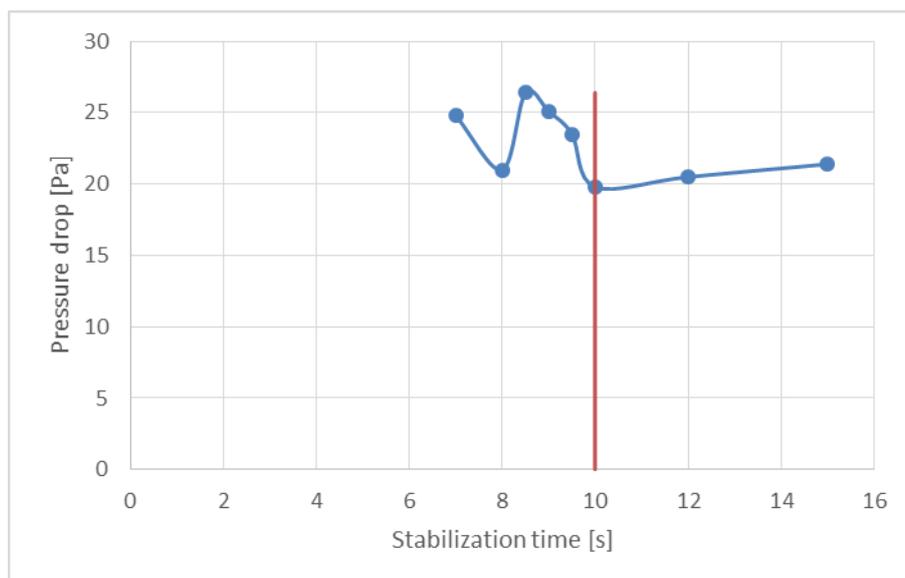


Figure 4-19: Graph representing the trend of the mean pressure drop as a function of the stabilization time

We can see the red line at value of 10 s that represent the right amount of time needed for stabilization in this specific cycle. Now we have found both filling and stabilization time.

The example reported is relative to the cycle D05NA but what described is repeated for all the created cycles in order to complete the study of times for the production and testing of the principal valve codes.

In this way theoretically we have all the parameters needed to set up the cycles (times, pressures and pressure drops); nevertheless a further operation for averaging the times is performed. The idea is to look at the influence of the volume on the filling and stabilization time when the filling pressure is the same. The data just calculated are plotted in a graph that shows the trend of the times (filling and stabilization) vs the volume filled (value coming from the analysis of valve codes with the use of the CAD software). For this goal different graphs are created where each one correspond to a specific working principle and filling pressure, these are shown below. The first three graphs are related to the cycles for the direct acting valves and manifolds associated with different filling pressure: Figure 4-20 represent the data with 5 bar of filling pressure, Figure 4-21 for 10 bar and Figure 4-22 for 15 bar. The last graph in Figure 4-23, instead, is the one proper of the test cycles for the combined operation solenoid valves and with pilot control always performed at 10 bar.

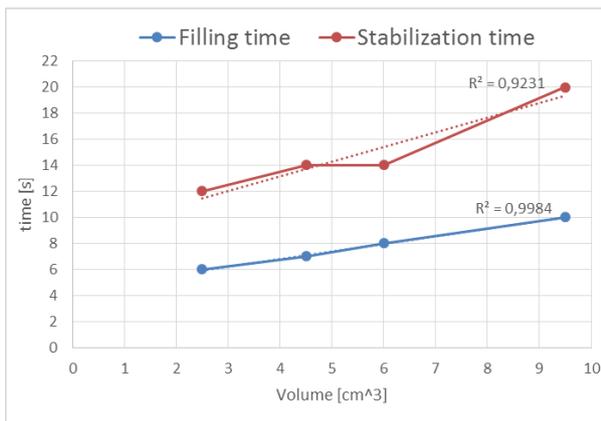


Figure 4-20: Trend of filling and stabilization time function of the filled volume for direct acting valves and manifold with filling pressure of 5 bar

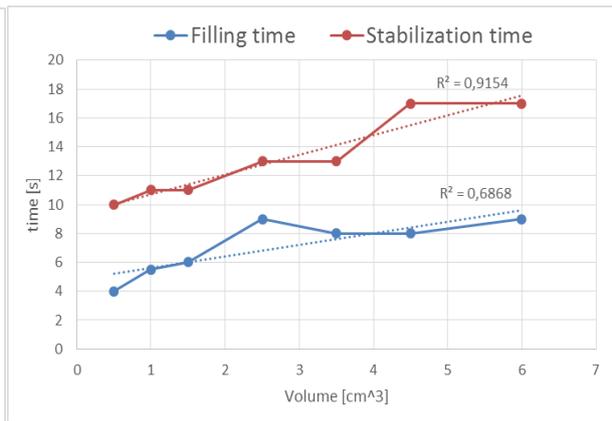


Figure 4-21: Trend of filling and stabilization time function of the filled volume for direct acting valves and manifold with filling pressure of 10 bar

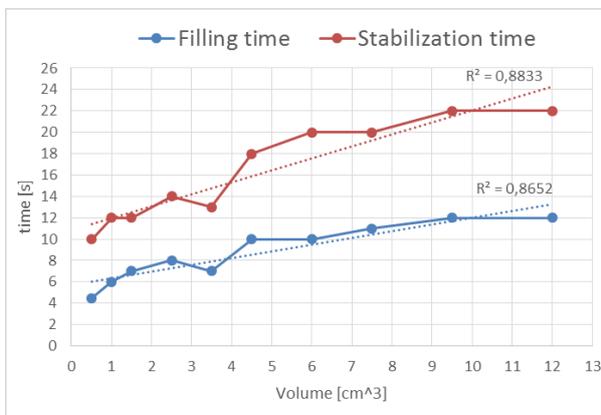


Figure 4-22: Trend of filling and stabilization time function of the filled volume for direct acting valves and manifold with filling pressure of 15 bar

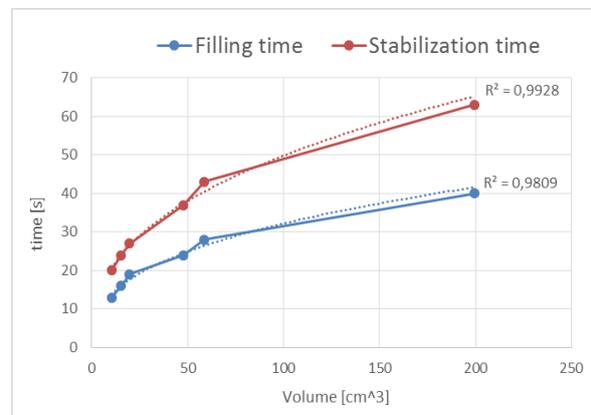


Figure 4-23: Trend of filling and stabilization time function of the filled volume for combined operation valves and with pilot control at pressure of 10 bar

In conclusion of the analysis it is possible to generate an interpolation of each series of data, this operation allows to average those data that are outliers, maybe due to specific conditions of the test in which we are not interested in. In this way the times for the cycles are derived from the interpolation curves according to the working principle, the filling pressure and the internal volume, so the data are a little be re-set with respect to the experimental results. This operation is useful, as already said, to average the results but also because the generated curves allow to generalize the analysis also at different volumes that could be needed in the future.

4.4 CREATION OF THE TEST CYCLES WITH ASSOCIATED PARAMETERS

At this point all the information related to the design of the cycles are available and have to be summarized in a table. The only difference to notice with the previous data is the value of the filling time that in this phase is increased of 1 s due to the fact that in the testing phase the operator checks the correct opening and closing of the valve with a permanent magnet. In this operation, not considered during the study of the cycle times, the valve is opened and so a part of the pressurized air flows out. Therefore the extended time takes into account the time needed for this procedure.

The summary table, shown in Table 21, reports the name of the created programs, the filling pressure of each one, the times for the cycle (filling, stabilization and test) and the maximum accepted pressure drop.

Cycle Name	Filling pressure [bar]	Filling time [s]	Stabilization time [s]	Test time [s]	Max pressure drop [Pa]
D05NA	10	6	10	4	55
D05OA	15	7	11	4	90
D05OB	15	7	11	0,4	450
D10NA	10	7	11	4	55
D10OA	15	7	12	4	90
D10OB	15	7	12	0,4	440
D15NA	10	7	11	4	55
D15NB	10	7	11	0,4	430
D15OA	15	8	13	4	90
D15OB	15	8	13	0,4	435
D20MA	5	7	11	4	20
D20NA	10	8	13	4	55
D20NB	10	8	13	0,4	420
D20OA	15	8	14	4	90
D25NA	10	9	14	4	55
D25NB	10	9	14	0,4	405
D25OA	15	9	15	4	90
D30MA	5	8	14	4	20
D30NA	10	9	16	4	55
D30NB	10	9	16	0,4	390
D30OA	15	10	16	4	85
D30OC	15	10	16	0,4	3265

Cycle Name	Filling pressure [bar]	Filling time [s]	Stabilization time [s]	Test time [s]	Max pressure drop [Pa]
D35MA	5	9	16	4	20
D35NB	10	11	18	0,4	375
D35OA	15	11	18	4	85
D40OA	15	12	20	4	85
D45MA	5	11	20	4	20
D50NA	10	15	26	4	50
G15OA	15	8	13	4	90
G20OA	15	8	14	4	90
G25OA	15	9	15	4	90
G30OA	15	10	16	4	85
G35OA	15	11	18	4	85
G40OA	15	12	20	4	85
G45OA	15	13	22	4	85
G50OA	15	15	25	4	85
S10NA	10	14	19	4	50
S15NA	10	17	23	4	50
S20NA	10	19	28	4	50
S20ND	10	19	28	0,4	40
S30NA	10	25	36	4	45
S35NA	10	27	40	4	45
S65NA	10	44	68	4	40

Table 21: Summary table of the main parameters for the new created cycles

Analyzing all the results shown in the table we can make some comments:

- It is decided to keep the same filling pressures as the ones of the actual test cycles. The same for the test time that remains equal to 4 s in most of the cases and equal to 0.4 s when the test verifies the sealing of a shutter with an hard material (ruby or teflon).
- The values of the accepted pressure drops are similar to the actual one but not the same, in particular: the limit for the test at 15 bar is quite increased (from 80 Pa to 90 or 85 Pa according to the volume), instead the limit at 10 bar is decreased (from 60 Pa to 55/40 Pa), the same for the test at 5 bar (from 30 Pa to 20 Pa). These new values for pressure drop limit have been done in order to provide a loss of 4 cm³/h, according to what was previously discussed about the relation between pressure drop and leakage.
- The filling and stabilizing times are generally higher than the actual ones. This means that currently in most of the cases the valves does not reach a situation of equilibrium during the leakage tests.
- The number of basic cycles is increased a lot: the cycles created for the most important codes are 43 against the old 29 basic cycles of which only about 10 are most frequently used. This was exactly one of the goals of the project, i.e. to create specific cycles for the different typologies of the tested valves and not

to use the same cycle for very different valves (different volumes or operating principle) as it has been done so far.

Regarding the filling and stabilization times, the problem is the need to find a good trade-off between the high productivity (that implies a short cycle time) and effectiveness of the valve testing (higher cycle time to reach the stability). The cycle times obtained from the analysis are the ones judged to properly perform the leakage test in complete stable conditions. On the other hand the increase of almost all the filling and stabilization times with respect to the actual situation would bring to an important increase of the times associated with the testing phase. To overcome this problem the idea is, in the first phase of new cycles implementation, to reduce these times of a 10% in order to be closer to the actual ones, accepting the fact that in this way, the pressure drop measured will be on average a little bit higher. Looking at the values of pressure drop obtained during the experimental study of times, it can be noticed that they are considerably lower than the limit of acceptability, on average around 50% of the limit value. For this reason it could be profitable reducing the cycle's times because in most of the cases also the increased value of pressure drop remains under the limit value of acceptability. In this way some seconds are saved at each cycle and we can also accept that few tests have to be repeated. Moreover it is planned to monitor in the first phase of the introduction of the new cycles the trend of the results in order to eventually correct a little bit the times reaching the best trade-off between high productivity and correct test execution.

A new table with the reduced times is generated and shown in Table 22.

Cycle Name	Filling pressure [bar]	Filling time [s]	Stabilization time [s]	Test time [s]	Max pressure drop [Pa]
D05NA	10	6	9	4	55
D05OA	15	6	10	4	90
D05OB	15	6	10	0,4	450
D10NA	10	6	10	4	55
D10OA	15	7	11	4	90
D10OB	15	7	11	0,4	440
D15NA	10	6	10	4	55
D15NB	10	6	10	0,4	430
D15OA	15	7	11	4	90
D15OB	15	7	11	0,4	435
D20MA	5	6	10	4	20
D20NA	10	7	11	4	55
D20NB	10	7	11	0,4	420
D20OA	15	7	12	4	90
D25NA	10	8	13	4	55
D25NB	10	8	13	0,4	405
D25OA	15	8	13	4	90
D30MA	5	7	13	4	20
D30NA	10	9	14	4	55
D30NB	10	9	14	0,4	390
D30OA	15	9	15	4	85
D30OC	15	9	15	0,4	3265

Cycle Name	Filling pressure [bar]	Filling time [s]	Stabilization time [s]	Test time [s]	Max pressure drop [Pa]
D35MA	5	8	14	4	20
D35NB	10	9	16	0,4	375
D35OA	15	10	16	4	85
D40OA	15	11	18	4	85
D45MA	5	10	18	4	20
D50NA	10	14	23	4	50
G15OA	15	7	11	4	90
G20OA	15	7	12	4	90
G25OA	15	8	13	4	90
G30OA	15	9	15	4	85
G35OA	15	10	16	4	85
G40OA	15	11	18	4	85
G45OA	15	12	20	4	85
G50OA	15	13	22	4	85
S10NA	10	12	17	4	50
S15NA	10	15	21	4	50
S20NA	10	17	25	4	50
S20ND	10	17	25	0,4	40
S30NA	10	22	32	4	45
S35NA	10	24	36	4	45
S65NA	10	40	61	4	40

Table 22: Summary table of the main parameters for the new created cycles with a reduction of 10% of the filling and stabilization times

5 PROJECT RESULTS IMPLEMENTATION

The last step stands in the real application of the results of the project. The process to gradually implement all the new improvements founded will take a long time. For this reason the thesis work focuses the attention on a so called beta implementation, a first attempt of application of the new cycles, and on the description of the future steps that will be performed in the following months.

5.1 RESULTS ANALYSIS

First of all we want to evaluate the goodness of the new performances, this is done performing a new data collection as done in chapter 2 for the current situation and then comparing the results. A batch of a specific valve code, already evaluated in the first data acquisition, is tested with the new specific cycles created and the data are collected. The valve code studied is the 5578, object of the analysis 3 (chapter 2.4.3), a 3 way valve that needs two different tests for the evaluation of leakage. Previously it was used the basic cycle 1A for both of the tests, instead, according to the results of the study, the new basic cycles associated are D05OA and D25OA, respectively for the test of the orifice and for the test of mechanical sealing and welding. If we compare the parameters of the cycles, shown in Table 23, we can see that the new cycles have limit of acceptability a bit higher than the old one instead the times are a bit shorter for the first test (D05OA, characterized by a small volume) and a bit longer for the second one.

	Cycle Name	Filling pressure [bar]	Filling time [s]	Stabilization time [s]	Test time [s]	t cycle [s]	Max pressure drop [Pa]
Old	1A	15	7	11	4	22	80
New	D05OA	15	6	10	4	20	90
	D25OA	15	8	13	4	25	90

Table 23: Comparison of the parameter between the old cycle and the new ones

Monitoring the testing of a batch with the new cycles and saving the results of ATEQ on a USB key it is possible to analyze the new performances. The macro-result of this analysis can be represented in the percentage of the tests with positive results vs the tests with negative ones, as reported in Table 24. To highlight the differences with the

current situation, the same table with the results of the classic cycle 1A is reported again in Table 25.

Test Result	N. of Occurrences	% of Occurrences
A	2011	
(AL)	1	0,05%
(PB)	1874	93,19%
(ST)	136	6,76%
B	1967	
(AL)	8	0,41%
(PB)	1675	85,16%
(ST)	284	14,44%
TOTAL	3978	

Table 24: Macro-results of leakage tests for valves 5578 with the new cycles

Test Result	N. of Occurrences	% of Occurrences
A	492	
(AL)	5	1,02%
(PB)	456	92,68%
(ST)	31	6,30%
B	541	
(AL)	1	0,18%
(PB)	420	77,63%
(ST)	120	22,18%
TOTAL	1033	

Table 25: Macro-results of leakage tests for valves 5578 with the old cycle

From the comparison of the two tables we can immediately see that in the new situation (on the left) the percentage of positive tests (PB) is increased for both the tests (from 92,7 to 93,2% and from 77,6 to 85,2%). Consequently the sum of negative tests (ST) and alarm of the instrument (AL), from our point of view the same situation due to the fact that they need a re-test, decreases. The data describing the actual situation with the old cycles contain also information regarding the exact value of pressure drop, this allows to evaluate also the percentage of the tests that give a pressure drop lower than 90 Pa, the new limit. This percentage is equal to 93.4% and 83.9% respectively for test A and test B. This means that comparing the dummy old situation (with 90 Pa as limit) with the new one, considering the same limit of acceptability, we have that in the test A the positive test percentage remains stable (from 93.4 to 93.2%) instead for test B increases (from 83.9 to 85.2).

But to evaluate the difference in term of productivity between the new situations with the old one we have to consider also the different cycle times in combination with the positive tests percentage. This operation is performed in Table 26 where two different comparisons are done for test A and B. For each cycle the times are reported obtaining the total cycle time, its inverse allows to obtain the number of cycles that can be performed in a unit of time, in this case in an hour. Then recalling the value of positive test percentage and multiply these last two values we obtain the throughput of the testing phase that, being this phase the bottleneck of the line, represents also the throughput of the whole line.

TEST A	Time [s]					cycles/h	% positive tests	Throughput [pz_OK/h]
	fill	stab	test	set-up	TOT			
Old (1A)	7	11	4	10	32	113	92,68%	104,3
New (D050A)	6	10	4	10	30	120	93,19%	111,8

TEST B	Time [s]					cycles/h	% positive tests	Throughput [pz_OK/h]
	fill	stab	test	set-up	TOT			
Old (1A)	7	11	4	10	32	113	77,63%	87,3
New (D250A)	8	13	4	10	35	103	85,16%	87,6

Table 26: Comparison from the productivity point of view, between the old and the new situation

The throughput in both of the cases (test A and B) increases, a lot in the first case and a bit in the second one. It is important to underline that also a small increase results in a considerable higher number of valves shipped taking into account the high number of ATEQ instruments working simultaneously all day in the company. Indeed there are 8 principal assembly lines and each of them has 4 ATEQ instruments; in the case of a valve that needs two different tests there are 2 instruments dedicate to each test. So a delta in the throughput of 7.5 units per hour, like in the case of test A, multiplied for 2 instruments multiplied for 8 lines means an increase of 120 u/h in the overall department or, expressed in a different way, over 2500 more units per month.

5.2 FUTURE DEVELOPMENTS

The main obstacle to overcome for the massive introduction of the new cycles is the actual management of the test phase completely manual and entrusted mainly to the experience of the operator. If this was good for the past years when the production volumes and the ranges of products were considerably lower than the actual ones, now a more automatize management has to be inevitably implemented. This is completely in accordance with the results of the project where, due to the wide variety of solenoid valves, a lot of different testing cycles are created. So it is impossible to think at their use with a manual selection both for time reasons and errors. Looking at this problem, the solution is the implementation of a specific software from ATEQ (I-Ateq) for the management of the measuring instruments through the use of a PC. The Figure 5-1 represents 4 different views of the software on the PC screen, it can be seen that I-Ateq can manage till 9 instruments simultaneously. From the PC it is possible to program the instrument, manage it and see in real time the execution of the different steps of the test cycle.



Figure 5-1: I-Ateq software for the management of the leakage test instruments, 4 different views

The main advantage of the software is the possibility to load the basic cycles on the instruments directly from the PC. This means that, through a barcode reader that identify the production batch, it is possible to automatically load the cycles querying a database that connects the valve codes with the test cycles. This method is certainly faster than the actual one but also, more important, it does not allow any human error in the selection of the cycle.

Another benefit in the use of the I-Ateq is the centralization of the managing of the basic cycle's parameters, i.e. each PC, when loads a cycle, refers to the same database containing the parameters. In this way we are sure that the cycles are performed in the same way in all the assembly lines and every change of some parameters can be easily done in the main database spreading the results on the whole department. Now instead the cycles with their parameters are saved on the ATEQ instrument and so the changes has to be done on each single machine increasing exponentially the time needed and the possibility of an error. Furthermore it is usual

that nominally the same cycle has different parameters in different instruments giving a not uniform procedure of testing.

The last important advantage is an easier traceability of the testing phase. The result of each cycle, reporting the exact value of pressure drop, is saved on the PC (and eventually directly on the company network) instead of on the instrument. The results are strictly correlated with the batch number and in this way the information related to each client order are accessible, also from remote.

Regarding the parameters of the created cycles, it is expected that during the implementation in the real production lines they have to be adjusted a little bit to reach the optimal situation. To help the performing of this operation it will be used a special platform, called Tulip, especially designed to show on a tablet the real time performances of the process. Monitoring the amount of re-test performed it is possible to immediately understand when the process is not optimized. In the same way the effects of any change in the configuration can be observed, evaluating the reaching of a real improvement of the situation.

As already said the new basic cycles created with this work are collected in a database that couples valve codes with testing cycles; this database is the starting point for the automatic selection of the cycles performed with the use of the I-Ateq. But it is clear that these cycles have to be considered only as a starting point for the definition of the testing procedure and the database has to be continuously update. Indeed the valves with low production volumes are not yet considered but when they have to be tested an already existing cycle has to be associated or a new one created. The same for the new solenoid valves designed for a specific request of the client, the idea is that at the end of the designing phase, together with the definition of the testing procedure already done in the past, the association of the valve with a specific cycle should be added in the database. In order to help with the creation of new test cycles it is created a worksheet that takes as input the characteristics of the valve (operating principle and inner volume) and test's conditions (filling pressure and leakage flow accepted) and gives as output all the cycles parameters needed for the definition of the basic cycle (times and pressure drop limit).

6 CONCLUSION

The main objectives of this work were the analysis and the reorganization of the leakage testing procedure for the valves manufactured by ODE. Beside them, other different results have been reached.

Starting from the beginning of the project, a first significant task was the study of the current leakage test system, the used instruments and the followed procedures. A more detailed study of the ATEQ instrument working and performances allowed achieving a better understanding of the performed cycle and to discover more possibilities of customization of the cycle depending on the specific needs of Ode. Particularly, the introduction of a function called “N tests” represent a big improvement in the productivity of the department. This function allows to automate the repetition of those tests that give as a result a pressure drop slightly higher than the limit. This repetition of the test on the same valve is something already performed manually by the operator because very often the repetition of the cycle brings to a lower value of pressure drop measured. The automation of this procedure first of all ensures the same behavior on all the production lines in the department, something not possible with manual operation, and moreover ensures a reduction of the times. This is because with the manual procedure the valve after the first test is emptied and then re-filled from the beginning, instead with the N tests function the valve is maintained filled with pressurized air and only the measuring phase of the cycle is repeated, avoiding filling and stabilization phases.

Then, experimental activities aimed to collecting some data about valve codes, measured pressure drops and influence of the cycle parameters allowed making a clearer picture of the testing method actually available. Analysis of the collected data outlined that the number of tests performed to check all the valves is significantly higher than the theoretical one, of about 20%; this extended testing reduces the productivity of the department. Looking to the results about rejected valves, it was observed a high amount of the so called “false negative”, because the pressure drop was only a bit higher than the acceptable limit, verified with additional testing in water. These are cases on which the modification of the testing parameters can be very effective, saving time and improving the productivity of the company.

From the performed experimental activity the product portfolio of the company was studied. In this way it is possible to generate specific families of valves which are the starting point of the database for the coupling of valve codes and basic cycles. The implemented approach is completely different from the existing one according to which few cycles were created for all the codes. The study instead pointed out that according to the characteristics of the valve, the new code will be associated to an existing testing family only if similar features are present (like internal volume, operating principle and accepted leakage), otherwise a specific cycle would be created.

In order to understand the relation between measured parameter for the leakage testing (pressure drop measured by ATEQ instrument during the testing) and the leakage flow, characterization of the reference instrument has been performed with certified flow loss and a flowmeter. .

It was found that the theoretical formula provided by the ATEQ can be used for the relation of pressure drop and leakage; the formula however has to be corrected with a further component that takes into account the influence of the filling pressure, not considered in the ideal situation.

In this way, starting from the declared performances of the valve, it was possible to define a new limit of acceptability for the pressure drop obtained from the leakage test, for different filling pressures.

Finally, the work allowed the generation of the new specific cycles that will be implemented instead of the actual ones. These new cycles have as a goal the improvement (quality and productivity) of the leakage testing phase and in general of the all department, setting the best parameters in terms of flow rate measurement and reduction of re-testing of manufactured codes. Another possible advantage is managing of an higher number of new created cycles with respect to the older ones; this would allow to have high customization with respect to the tested products, an essential characteristic looking at the high variety of codes produced.

A first application of the new designed codes has been performed on a three way valve, showing reduction of the time required for batch testing with a gain on the department productivity of about 4% for that code.

The next phases of the project will be the monitoring of the new added codes and evaluation of the performance of the revised leakage testing procedures. Moreover, in

the next months further action will be performed in order to reach an increasingly automated and optimized testing phase.