Kaunas University of Technology

Faculty of Mechanical Engineering and Design

The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing

Master's Final Degree Project

Daumantas Matulis

Project author

Assoc. prof. dr. Kazimieras Juzėnas

Supervisor

Kaunas, 2020

Kaunas University of Technology
Faculty of Mechanical Engineering and Design

The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing

Master's Final Degree Project

Industrial Engineering and Management (6211EX018)

Daumantas Matulis
Project author

Assoc. prof. dr. Kazimieras Juzėnas
Supervisor

Assoc. prof. dr. Rūta Rimašauskienė
Reviewer

Kaunas, 2020

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Daumantas Matulis

The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing

Declaration of Academic Integrity

I confirm that the final project of mine, Daumantas Matulis, on the topic "The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by Law) have been paid to anyone for any contribution to this project.

I fully and completely understand that any discovery of any manifestations/case/facts of dishonesty inevitably results in me incurring a penalty according to the procedure(s) effective at Kaunas University of Technology.

____________________ _______________

(name and surname filled in by hand) (signature)

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Task of the Master's final degree project

Given to the student – Daumantas Matulis

1. **Title of the project –**

The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing.

(In English)

Bandymų, skirtų vandens skaitiklio lieto plastiko korpusui, sprendimų kūrimas.

(In Lithuanian)

2. **Aim and tasks of the project –**

Aim:
To develop quality problem solution for plastic injection moulded water meter housing.
Tasks:

1. To research conditions and parameters influencing water meter housing quality problems.
2. To propose solution to solve quality problem of water meter housing.
3. To calculate cost of proposed quality problem solution implementation.

3. **Initial data of the project –**

1. Proposed facilities must fit into four square meters of floor space.
2. Water meters must be tested in the temperature range from 20 to 70 degrees Celsius.

4. **Main requirements and conditions –**

None.

Project author	Daumantas Matulis		
	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	assoc. prof. dr. Kazimieras Juzėnas		
	(Name, Surname)	*(Signature)*	*(Date)*
Head of study field programs	assoc. prof. dr. Regita Bendikienė		
	(Name, Surname)	*(Signature)*	*(Date)*

Daumantas Matulis. The Development of Testing Solutions for Plastic Injection Moulded Water Meter Housing. Master's Final Degree Project, supervisor assoc. prof. dr. Kazimieras Juzėnas; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.
Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: plastic injection, parameter setup, testing method, quality problem, meter housing, extreme conditions, development.

Kaunas, 2020. 55 pages.

Summary

The master thesis aims to develop quality problem solution for plastic injection moulded water meter housing. In the project, an analysis of similar plastic injection moulding process problems is done. Results of similar problem solution implementations are discussed. Based on literature research and analysis of scientific publications, the most influential moulding parameters are selected for the experiment to find the best parameter setup. The experiment is performed by producing meter housing samples using several different parameter setups. The best parameter setup is applied in the production to increase water meter housing quality. After improving quality in the plastic injection moulding process, testing of the quality increase is done using developed methods. Based on the testing results, a proposal of a new testing bench is made to reduce the quantity of outgoing faulty water meters and increase testing capabilities. Proposed quality problem solution advantages are presented. The cost of solution implementation is calculated together with meter replacement cost. Suggestions for future work are made based on this project results.

Daumantas Matulis. Bandymų, skirtų vandens skaitiklio lieto plastiko korpusui, sprendimų kūrimas. Magistro baigiamasis projektas, vadovas doc. Kazimieras Juzėnas; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.
Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: plastiko liejimas, parametrų rinkinys, testavimo metodai, kokybės problemos, skaitiklio korpusas, ekstremalios sąlygos, sprendimų kūrimas.

Kaunas, 2020. 55 p.

Santrauka

Magistro darbo tikslas yra sukurti vandens skaitiklio korpuso, lieto iš plastiko, kokybės problemos sprendimą. Šiame darbe yra analizuojamos susijusios plastiko liejimo proceso problemos ir aptarti kelių skirtingų problemų sprendimo būdų pritaikymo rezultatai. Remiantis literatūros apžvalga ir mokslinių publikacijų analize, tyrimui pasirinkti didžiausią įtaką gaminio kokybei turintys plastiko liejimo proceso parametrai. Tyrimas yra atliktas pagaminant vandens skaitiklio korpuso pavyzdžius naudojant skirtingus liejimo parametrų rinkinius. Naudojantis tyrimo rezultatais, išrinktas geriausias parametrų rinkinys, kuris yra pritaikomas gamyboje siekiant pagerinti vandens skaitiklio kokybę. Pagerinus plastiko liejimo proceso kokybę, atliktas gaminio kokybės testavimas naudojant naujai sukurtus metodus. Įvertinus testavimo rezultatus, siūlomas naujo testavimo stendo įdiegimas norint sumažinti iš gamyklos išeinančio broko kiekį ir padidinti prietaisų testavimo pajėgumą. Taip pat, aptarta siūlomo problemos sprendimo nauda kartu su naujai sukurto problemos sprendimo įdiegimo kaina. Įvertinti dėl broko galimi finansiniai nuostoliai ir naujai diegiamo testavimo stendo atsipirkimas. Taip pat, darbe pateikti pasiūlymai tolimesniam darbui.

Table of Contents

List of figures

List of tables

Introduction

The importance of product quality in manufacturing companies is one of the main essential aspects. High product quality gives a competitive advantage amongst competitors and builds a trusting relationship with existing clients for a company. When quality problems occur outside a company reported by the client, it is crucial to take problem-solving actions and maintain communication with the client about the current situation. Sometimes company product has quality problems which occurs only in specific conditions. In this situation, the company need to react with confidence and provide further actions which will be performed to solve the problem. When manufacturing processes seems to be perfected, unfortunately, it is hard to think of all possible conditions where product will be exploited. In our situation, dealing with a problem to eliminate it from production requires specific decisions based on investigation of returned products. Analysis of scientific sources related to this topic shows that there are innovative ways for solving similar complex quality problems. It is essential to apply the right manufacturing process improvements and testing solutions. Recreation of a real-life environment as a solution for testing is involved in sorting faulty meters from good. Testing methods created to assure product quality are allowing the company to keep all faulty meters from reaching clients. The development of a new test bench shows novelty of the project by solving quality problem appearing only in a humid environment with significant temperature changes.

Hypothesis: Quality problem of plastic water meter housing can be solved by improving plastic injection moulding process and applying new testing methods.

Project aim: To develop quality problem solution for plastic injection moulded water meter housing.

Project tasks:
1. To research conditions and parameters influencing water meter housing quality problems.
2. To propose solution to solve quality problem of water meter housing.
3. To calculate cost of proposed quality problem solution implementation.

1. Review of the plastic injection moulding process and quality assurance methods

Plastic injection moulding could sound very complicated to a lot of people. Still, it is a trendy manufacturing method used to make a vast amount of everyday usage things in people lives. It is used for manufacturing at first glance small, manageable parts and things, to large and complex parts and components. Plastic injection moulding is a widely used manufacturing method with a big amount of possibilities. Stated below are just a few areas of manufacturing things seen every day and made using plastic injection moulding technology.

1.1. Overview of the plastic injection moulding technology

There are six most common types of plastic used in plastic injection moulding. ABS stand for tongue-twisting Acrylonitrile-Butadiene-Styrene, and it works for producing parts such as dashboards, switches, handles and so on. Things made from this type of plastic can be found in people homes or cars. Polypropylene is another type of plastic which is suitable for manufacturing food packaging or medical containers. Nylon is a synthetic thermoplastic polymer that has good resilience against chemicals and heat. It can be found in engines and other impactful environments. Polycarbonate is used for making cd’s, and it is known for its natural transparency. Polystyrene is famous for making everything from toy figures to medical devices. It is also easily manageable when heated to liquid form, so it makes the manufacturing process less complicated. Selection of materials for specific products is based on its parameters such as flexibility, cost, hardness, and other physical properties. For every field of products, there are different environmental requirements which cannot be met by all types of plastics [1].

Plastic injection moulding is only one from many different ways to produce plastic parts. There are other technologies such as blow moulding. It is popular in making parts such as bottles. In the beginning, there is one piece which is usually a plastic tube. Then by heating a piece and blowing hot air into it, a part can be transformed into desired shape and geometry. Compression moulding is another technology where heated plastic is injected inside the mould and shaped by pressing it from both part sides. The final form of the part depends on the design of the mould. This process is cost-effective, efficient and flexible. Extrusion moulding is unique because the shape of the die, not the mould, determines the geometry of the final product. Extrusion moulding is similar to injection moulding, but it is much more suitable for long parts. Rotational moulding is very different from others because this technology is based on rotational movement. It is using its rotational force to form walled parts very evenly inside. Lastly, there is a plastic injection moulding technology which is analysed in this project. [2].

There are different types of plastic injection moulding machines used for this type of production. Hydraulic plastic injection moulding machines have a benefit of enormous power, cheaper price tag and less expensive, stronger parts. Another type is the electric injection moulding machine. Its benefits are lower downtime, cleaner, faster process, and environmental friendliness. Last class is hybrid machines which combine the benefits of the first two. It has a price tag in between of hydraulic and electric with greater efficiency, lower downtime, and faster production. Hybrid injection moulding machines are famous among manufacturers of medical devices [3].

Plastic injection moulding is a manufacturing process for producing parts by injecting melted plastic into a mould. Plastic injection moulding can be performed with a certain material which is thermoplastic and thermosetting polymers. The plastic material is sourced into a heated barrel, mixed using a helical shaped screw, and injected into a mould cavity, where it cools and hardens to the configuration of the cavity, forming a specific desired part or product. After a designer or an engineer designs a product, moulds are made by another mould making company, usually from steel or aluminium, and precision-machined to form the features and parameters of the wanted part.

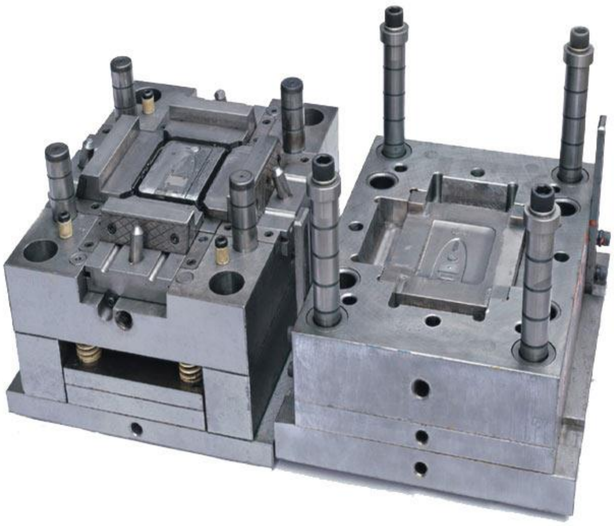


Fig. 1. Plastic injection mould [4]

The design process of parts which will be injection moulded must be precise in order to assure the correct moulding process. Properties and parameters of the machine, part design, shape, material, also the mould functions and materials need to match for a smooth process. This whole process strongly depends on the quality of relationships between the entire system, which includes mould (figure 1), machine (figure 2), and the desired part itself.

Fig. 2. Plastic injection moulding machine [5]

1.2. Different fields of usage

Inside a vehicle, people always see components and parts made by plastic injection moulding. For example, automotive dashboards, bumpers, and other elements are manufactured using this production method. Toggles for operating windows, radio, climate controls, bumpers, mud protectors, some connection parts are usually produced using plastic injection moulding technology. Lids and packaging containers of all sorts are made using plastic injection moulding. Another widely used products made using the same technology are plastic bottle caps, plastic cup lids and the lids for drug packages. Bottles for water and containers to store food, also cases to keep paint or other chemical liquids are produced the same way. The electrical switches for turning on the lights or to power up electrical devices such as washing machine are made from injection moulded plastic material. Entire electrical systems in company facilities or people homes depends on plastic injection moulding to have reliable and high-quality components. The healthcare industry uses plastics more compared to other sectors because plastics are versatile, lightweight, and sanitary. Lots of medical devices used in hospitals and other health care institutions are made using plastic injection moulding. That includes plastic syringes, containers and other tools used in medical procedures.

With this wide range of products and things used every day by almost everyone, all these parts require different quality and different environment for the manufacturing process. For production of simple buckets, hygiene and other requirements are not that important. Still, when talking about containers for food or medical devices, quality requirements, environmental conditions, and standards are stringent. To assure the required quality, companies need to use high-quality moulds. The relevance of this topic is evident because the majority of companies and industries rely on plastic injection moulding.

The quality assurance is the main factor to guarantee competitiveness and customer attractiveness of a company which produces plastic injection moulded parts. In today’s world, all of the necessary information is available to learn how to assure the usage of tools in the best way possible. This project analyses the best and most common ways to ensure the high quality of plastic injection moulded parts.

1.3. Other methods to assure quality

Companies face problems and need new solutions to improve the plastic injection moulding manufacturing technique. The relevance of this topic is emphasized by many scientific sources proving this point. Scientists and companies are always trying to improve and find more innovative ways to make the injection moulding process better. Inventions of new mould cooling ways, the analysis of parameter change impact to the final product quality, also the study of quality stability throughout the process are general topics.

In the article about monitoring and dynamic control of quality stability for the injection moulding process, the rising demand of production speed, higher quality and more complex products impact on today’s manufacturing quality stability problem is discussed. The problem is to keep high-quality stability when reaching higher process speed, shorter cycle times and making every other process more efficient and less time-consuming. This research presents the quality prediction model and the control method. [6]

Another relevant topic of plastic injection moulding process improvement and quality stability assurance is mould cooling systems. This article presents the possibilities and the advantages of conformal cooling of the forms comparing them with conventional cooling forms. The goal is to compare the impact of conformal and conventional cooling on plastic products, the distance of the cooling channels between each other and the production capabilities. It was developed by looking at the impact of technical and technological parameters on the quality of the part by comparing the length of the cycle to make one part on both cooling systems [7].

Injection moulded plastic parts are changing their dimensions while cooling down. It is a common problem to control this process and keep details in the right and desired shape. This process is called warpage. The warpage means deformation or uncontrollable change of the shape. The article about deformation analysis of plastic parts warpage process suggests the innovative mould design to solve this problem which is hard to control. The effects of mould temperature, holding pressure, and the glass fibre structure of the material were analysed using different gate types in the mould. Also, it shows a new specific software developed to evaluate the warpage of the plastic part. The Moldflow™ software has a good beginning towards this topic, because using this programme together with personal experience and calculations, the opportunity to predict some ways of part shrinkage and warpage is created [8].

There is another side of the plastic injection moulded part quality because, besides the cooling, several different factors are impacting the moulding process quality. In this manufacturing process, the mould has a massive impact on the whole process quality. The process speed and reliability depends on the mould quality. Complexity of the part relates to what type of mould is used for the production. Usually, it is a straight connection between the quality of the desired part and the quality of the mould. The company would never buy the high-quality and expensive mould for a simple part which does not require precision. For producing the high-quality, precise part, the company would purchase costly and well build mould because, in the end, this is the main component in this manufacturing process. If the company has a machine with massive potential in manufacturing efficiency but uses a poor quality mould, production line capabilities are going to waste. The essential task is to make the system to match its components.

One more problematic field for assuring the mould quality is to keep the inner surface the highest possible quality and prevent it from any damage. It is one of the main factors influencing the surface quality of a finished part. It mostly depends on the raw material used in the process. Companies are using composite materials based on polymers reinforced by hard and abrasive ceramic fibres, whiskers, or particles. In the article about the mould ware, the experiment is done analysing the different raw material impact to the injection chamber wall surface and what consequences it has towards the final part surface quality. The research states that when working with a raw material, the manufacturer of the mould must apply the additional hardening to the mould forming part surface, because after a short period, the surface roughness of the part increases significantly and it appears evenly [9].

The parameters, such as the mould temperature and the injection pressure, also have a significant impact on the final part quality. For different types of thermoplastics, changes in these parameters cause various consequences. The melting temperature of the injected plastic affects the shrinkage of the part, and the pressure defines the absolute geometry accuracy of the part. The article about the investigational experiment, which is done with several different types of plastics states that when producing a mould, a company must consider what kind of plastic will be used with it. A company must consider the mould characteristics to match a specific type of the plastic to get the best results in the final quality, geometry, and physical abilities of the part [10].

When producing the parts in large quantities at very high speed, for example, the plastic bottle caps, one of the commonly used technologies to assure the mass production part quality is using the conveyor which directs all of the moulded parts into one line. By creating this placement, the smart camera scanning technology can be implemented to film and measure the quality of the piece. The desired dimensions are selected and configured in the system. It can detect all of the defective parts by measuring and comparing it to the etalon. After sorting the good and the flawed quality parts, the system directs the components to two different containers dedicated for the excellent and ready for packaging parts and the ones which dimensions are not inside the tolerance range and look of the surface quality is not satisfying. The defective parts can be recycled and used again, producing the same component from the beginning. The recycled material can be used only in a specific percentage mixing it with the fresh raw material.

To conclude this part of the project, the analysis of different methods of the process, fields of usage and different applications of all types of the raw materials and the moulding technologies was made. The different applications of how to assure the quality of the mould, the quality of the final part, and the more efficient manufacturing process were covered.

2. Methods of product quality improvement

The novelty of the research can be proven by presenting how essential and widely used this manufacturing technology is these days. The plastic injection moulding has many advantages over the other manufacturing processes and techniques, but it also has a lot of unanswered questions and unsolved problems. The novelty of the research is finding a new way of solving the common problem related to the plastic injection moulded part quality assurance. It can be done throughout the whole process in a few different ways. For example, there is a new method for the automated design of the cooling system in injection mould based on the geometry of the plastic part. The algorithm recognises certain topology of the piece, gathering its depth map and detecting the areas and the other details which are hard to cool down. The algorithm collects the data of the surface heat map and using this information estimates the needed parameter setup for the specific cooling zone. In a further phase, the parameters of the cooling system, for example, the channel diameter or the channel separation, are taken by the algorithm for calculations. A second genetic optimisation algorithm makes the balance between the selected parameter setup and the zone which need to be cooled the most. The result is the design of the cooling system with the same performance as the conformal system. The data gathered in the design can be used later for other calculations [11]. The plastic injection mould cooling channels are shown in figure 3.

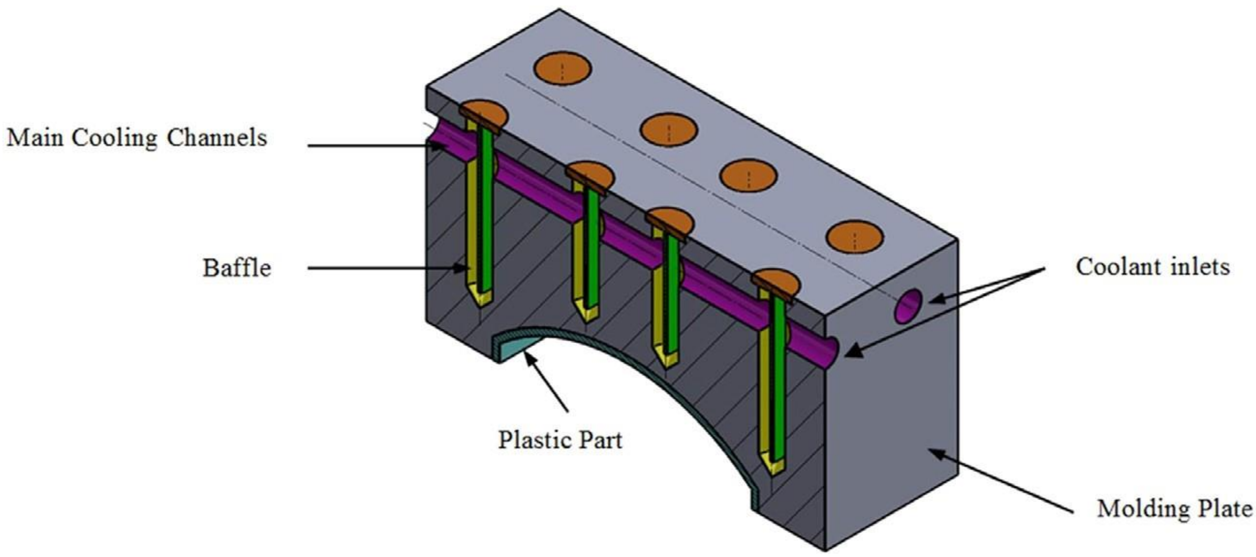


Fig. 3. Plastic injection mould cooling channels [11]

The novel aspect of this research is the newly created and presented artificial intelligence assisted system for the plastic injection moulding. There is the article about implementing the smart system in the plastic injection moulding process by using the temperature and the pressure sensors for keeping track of these parameters all the time and storing them into the database in which the analysis of the process can be done. This project is done regarding the problem of keeping the same quality through all the cycles. The method of the plastic injection moulding is not that stable, and the parameters can change during the more extended periods. This factor creates the problem of keeping the quality of the finished product the same all the time. The Moldflow™ software was used for a prior understanding of the impact between the parameter changes and the final product quality. Using the sensors for the temperature and the pressure parameters, the company can collect the data about the variations of these parameters. Pressure sensors, mould temperature sensors, holding pressure sensors and speed sensors are collecting the data. The machine controller usually controls these parameters. Then the other parameters which cannot be measured are calculated using the smart control system. When all of the data is collected, the algorithm is created to generate the reference model. By constant monitoring, the artificial intelligence control system can always check the data gathered from the sensors and by using the reference points of input parameters, it can continuously control the changes of the parameters to satisfy the desired quality tolerance [12].

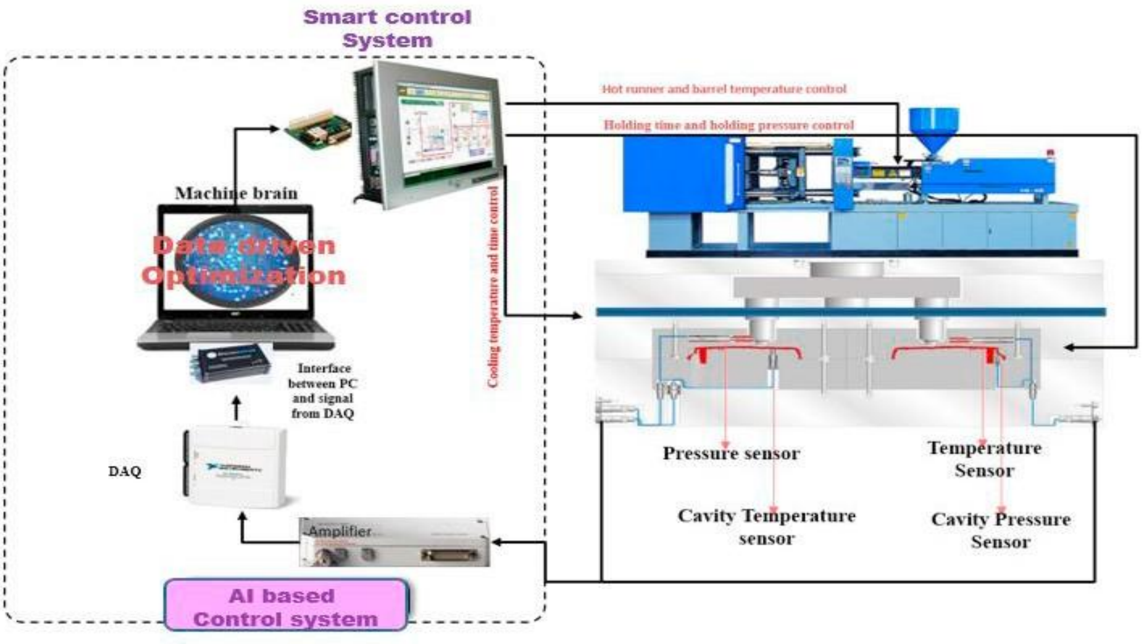


Fig. 4. AI-based smart control system [12]

These two articles show the novelty of this project by highlighting the most relevant innovative solutions to the most common problems in the plastic injection moulding process. This process is continuously improved and developed to reach new levels of stability and quality of the process. The research of a similar problem solution is analysed further in this project.

2.1. Different testing solutions

The novelty and the importance of creating the testing methods for the final product quality assurance is evident because very often, companies must create new and individual solutions for different problems of the product. There are standardised tests and testing methods to achieve some specific certificates for your products in various cases. Testing methods strongly depends on products purpose and exploitation conditions. For some plastic injection moulded products, additional testing is not required because it is enough to do specific tests to get needed certificates. Sometimes it is enough to send the product sample for testing, according to certificate requirements, to the independent laboratory. The independent testing service provides testing results and evaluations of the product performance. There are different requirements for various products in all regions of the world. The company decides which tests are needed to be able to sell the product in that region.

The other case is that sometimes the standardised test used in getting specific certificates on some different standard approvals is not enough to be sure that the product will perform as expected in different working environments. The novelty is well proven because in many cases, the company needs to design their testing methods, equipment, and quality assurance solutions. Especially when selling the device which will be exploited outside with crucial temperature changes, it is the responsibility of the company to make sure that the product will not fail to perform in those conditions. It is not easy to predict every worst-case scenario. Still, the company must try to simulate all possible ways to test the device to avoid bad consequences later, after the client has negative complaints. After researching what the most dangerous conditions and factors for the device are, the company must decide what testing solutions and methods will be applied to the product manufacturing process. It must be done to be sure about the client satisfaction. The selection of testing methods for products is based not only on the working or usage environment but also on the primary function. If the product is used not as a static part of some system but by the people at their homes, all possible actions must be done to be sure that the product will not break. It must hold pressures or different forces applied to it in its natural state.

Even when not thinking about the final product usage in the client's hands, the company can find reasons to test its manufactured parts properly. When the piece is used in an assembly, poor quality of one component could cause problems of the whole system assembly, damage other assembly parts or make the assembled system or mechanism to fail tests. The article about the extreme installation environments proves this point. It states that the company should not fully trust existing test standards because it can give false self-confidence about the product performance. The challenging installation and exploitation environments are things that the manufacturer must think of in the design stage when designing a new product. Of course, it is impossible to think about every possible outcome in advance. Still, a suggestion would be to communicate with the potential or already existing client to discuss and discover what additional testing of the product and design solutions must be applied and created to assure the desired quality of the product and the long-lasting product performance [13].

3. Research on plastic injection moulding process quality improvements

The plastic injection moulding manufacturing has several areas for improvements. One of the most common problems having place for improvement is the part cooling. The plastic injection moulding has four main abstract stages. The first one is melting the raw material, the second one is the injection, the third is the cooling, and the last one is the ejection. Not to mention other processes that have a significant amount of impact on the quality of the final part, cooling is one of the most important ones. When the company uses the plastic injection moulding technology, the goal is to benefit from it as much as possible. Every parameter must be optimised to the maximum to reach the desired process effectiveness. When the discussion about the cooling process begins, everything gets difficult. After the injection stage and the forming of the part, there are two different ways to go from here. The company can choose between setting a longer time of the piece to cool inside the mould or can take it out early and let it cool down in the ambient conditions. The first way is much safer, but it takes more time, and time in the plastic injection process, plays a vital role because every second counts. The second way saves a lot of time but has a problem that the plastic cooling down in the ambient temperature starts to deform and lose its original shape. Of course, the problem depends on the characteristics and parameters of the part. The plastic always deforms when cooling down. The goal is to avoid this problem. The company needs to find the best point in which the shape of the final part is the best, and the process is time-efficient. This topic is analysed in the article about the plastic injection moulded part cooling. It describes that the software and related programs with simulations can predict the part cooling behaviour only inside the mould. Still, when the part is cooled down outside the mould, it creates the vast and complex problem to predict how the piece will deform and change its shape. In the article, the authors suggest the Moldflow™-Ansys™ integrated FEA method to simulate the air-cooling process so that the deformation of the ejected part can be considered at the early design stage and the quality of the component can be ensured with the shortest cycle time. The proposed method uses Moldflow™ and Ansys™ by feeding Moldflow™ simulation results as the state data set into Ansys™ for the air-cooling created simulation. With the real testing product, when the part is ejected at a high temperature, it is possible to get positive and accurate results. The cost of the cycle time can be estimated and considered in the mould design stage. The better design stage gives a shorter cycle time and a lower price from the beginning of the process. It is better than optimising the existing moulding process or making changes to the design [14].

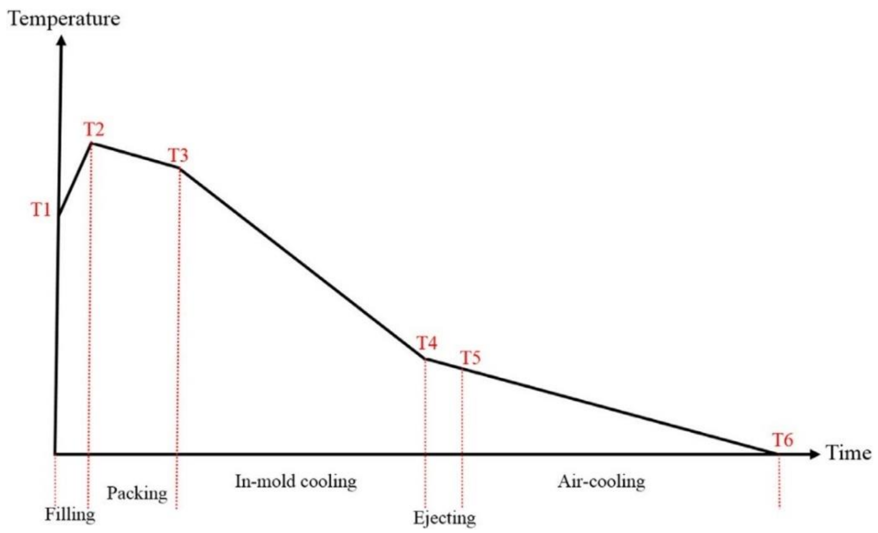


Fig. 5. Plastic injection moulded part temperature changes during the process [14]

With the presented simulation software, it is possible to calculate and predict how the material will act during the cooling process. The software is able to simulate the deformation of the part shape while it cools down. The task is to be sure that the part is cooled down enough for the ejection. After the ejection stage, the piece is left to cool down in the ambient temperature. The real goal is to find the right timing when to eject the part from the mould. This research describes only the theoretical way to make the problem possible to solve, but it requires further study. Today, the best way to assure the quality of the plastic injection moulded part is to find the right time to keep the part inside the mould for cooling to be safe to eject and do no damage or deformations to the shape of the piece. The right balance between the in-mould cooling time and the air-cooling time must be achieved in the plastic injection moulding technology.

Besides the cooling stage, there are other parameters which have a significant impact on the part and mould quality. The most critical part of the mould is the matrix of the cavity. It has a surface which is always in contact with the heated plastic during the production. The research was done to investigate what impact the different plastic material has on the matrix surface. There are several different coatings for the matrix surface to be protected from any damage of the plastic material. So, the experiment was done with several materials and coatings. Causes of the friction between the plastic and matrix surface will not do any apparent damage which can be seen with the naked eye. The investigation was done in the microscopical level where the smallest damages are visible. The purpose of the experiment was to create a new special chameleon coating for the matrix surface to adjust it for different raw plastic materials and to have the required resistance [15].

3.1. Final part testing solutions

Manufacturing parts using the plastic injection moulding usually requires a deeper analysis to assure that the final product meets the desired quality standards. There are a lot of ways to change the mould design to improve the quality of the product. All root causes of problems that the company is facing must be found to make real improvements. During the production, the manufacturer must be sure that the part is the highest possible quality. Certain ways for testing the final product must be created. It is not complicated when only one moulded part is taken into consideration. It can easily be measured regarding required dimensions, checked if everything is in order, but when the company is producing the more complicated part or even the whole assembly of elements, it is getting much harder to assure desired quality. Of course, it depends on the purpose of the finished product. For example, there is a method for testing the tightness of water-conducting components in a housing created to test the tightness of products which contains water pressure inside. It offers mounting certain sensors to detect leaks in the product or in the system in which tested product is mounted. Testing is a crucial part of the thriving manufacturing, mainly when the company is producing assembly products which will be used in challenging environments [16].

4. Engineering method to solve a similar problem

The problem companies are facing today is how to assure the plastic injection moulded part quality. This problem does not appear in the production with long cycle times. When cycle time is extended, the part can be cooled down much more inside the mould and can have less deformation or risk of losing the desired shape. Unfortunately, a long cycle time is not a valid solution for the competitive manufacturing. Every second counts so, to be profitable and productive, the company must shorten the production cycle time as much as possible. There is a possibility to achieve some benefits by playing with process parameters of the machine, but it causes the loss of time at the cooling stage. The cooling is a crucial factor in the plastic injection moulding because, on this parameter, the quality of the part depends the most. In the scientific article about the cooling process of the plastic injection moulding, the author is comparing what benefits conformal cooling has on the part quality and the production time compared with the conventional cooling method [7].

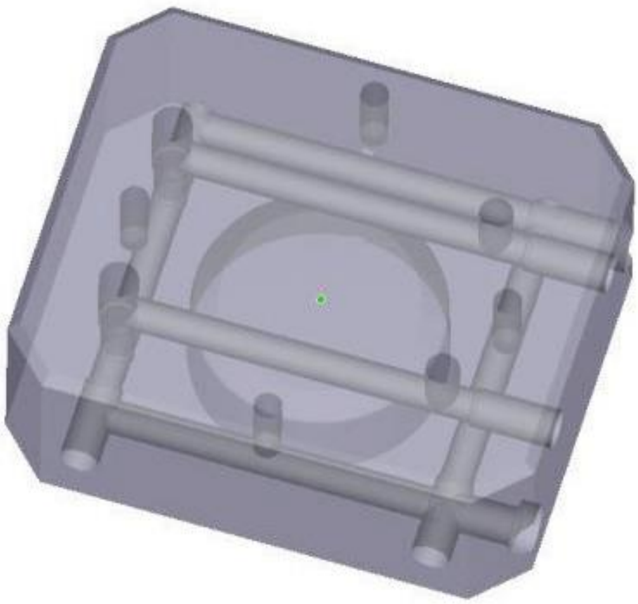


Fig. 6. Conventional channels [7]

In the picture above, typical conventional cooling channels inside the plastic injection mould are shown. Typically, the cut view of the part would be like the one presented in figure 6. These cooling channels are widely used because it is easier and cheaper to manufacture. So, this area was taken into consideration of the research as a potential site to be improved. By improving cooling channels, better results in the product manufacturing cycle time and the effectiveness of the process might be achieved. So, to improve this area, conformal cooling channels are taken into consideration.

The cooling channels are designed to supply the cooling fluid in the shortest possible distance from the mould wall and to follow the surface shape. The conformal cooling of the form offers completely new possibilities for the mould tempering that could never be reached while using the conventional cooling [7]. The process of creating the design of these cooling channels is very complicated. There is a cutting-edge technology using the innovative principle of the direct metal laser sintering patented by EOS. It is almost like the 3D printing, but in this technology, it is the sintering of the metal material. By using advanced machines, it is possible to monitor the manufacturing process and achieve the better quality continuously.

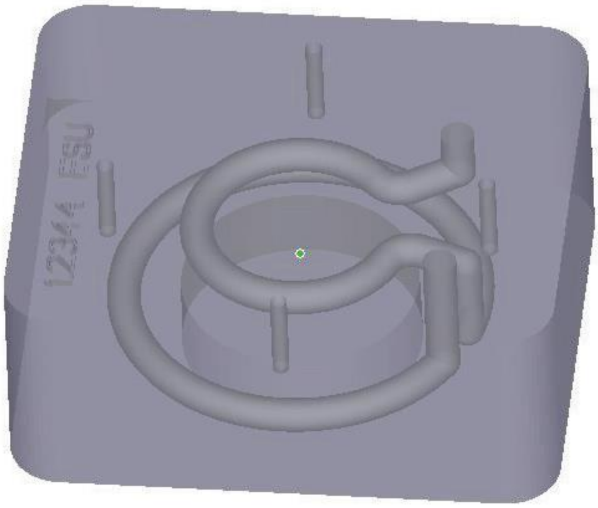


Fig. 7. Conformal cooling channels [7]

In figure 7, cooling channels in this type of the mould cavity are entirely different and follows the part shape. With this design, the company face other problems, but these problems can be solved with the accurate designing of the conformal cooling channels. When designing the conformal cooling channels, the right distance of channels must be kept from the cavity wall to assure even cooling effect from all sides. The tricky part is to calculate what space between the cavity wall and the cooling channel has to be left to make sure that the metal structure in between does not get damaged or lose its mechanical characteristics. After designing and manufacturing the conformal cooling channels inside the mould, the mould itself must be produced and examined to investigate the benefits gained from implementing this new technology. So, actual benefits were reached, and it showed a significant decrease in the production cycle time, reduction of the shape deformation and overall speed of the cooling was increased by 20%. The quality of the final part was much better after a shorter time of production. It shows that by using this method in the plastic injection moulding, it is possible to make the production cycle time shorter by increasing the overall quality of the part. It is a significant accomplishment and improvement. Even though the manufacturing of conformal cooling channels inside the mould is much more complicated, it is well worth it because benefits are much higher. The implementation of this cooling method inside the mould, provides the possibility to solve quality problems of cooling parts which have a complex shape and hard to reach surfaces.

The application of conformal cooling channels is complicated and requires a new mould design. However, there are ways of solving quality issues of the final part. The AI-based smart control application in the plastic injection moulding process has already been discussed. When the company faces quality assurance problems or process effectiveness problems, there are ways to solve it in the future when ordering new moulds by making design improvements, adding new coatings and features. The implementation of the smart control system can be done in the already manufactured and working plastic injection system, which includes the mould and the machine. The plastic injection moulding process requires constant monitoring to make sure that all final parts are in the same quality range. With high temperatures and high pressures, there is a variation of parameters appearing in the process. The implementation of smart control AI-based system in already working machine creates the ability to transfer workload and risk of human mistakes to the machine. Without this feature and the improvement, the operator of the device must do constant quality checks on the final part. By installing necessary sensors in the right positions, the data of the most influential parameters changing during the process can be collected. The smart control system collects available data and calculates parameters which cannot be measured. When the final product quality reaches the desired level, the system creates reference points and adds the tolerance range in which measurements can vary to make sure that product quality is at its best. When parameters start to overcome its limits, the AI-based smart control system can apply corrections and do it repeatedly assuring that the process will keep going with the best input parameters. The advantage of this system is the ability to change process parameters according to the deterioration of components and subsystems. It can also indicate when some dramatic changes happen and prevent the subsystem from failing or crashing. The scheme of the AI-based system working algorithm is presented in figure 8 [12].

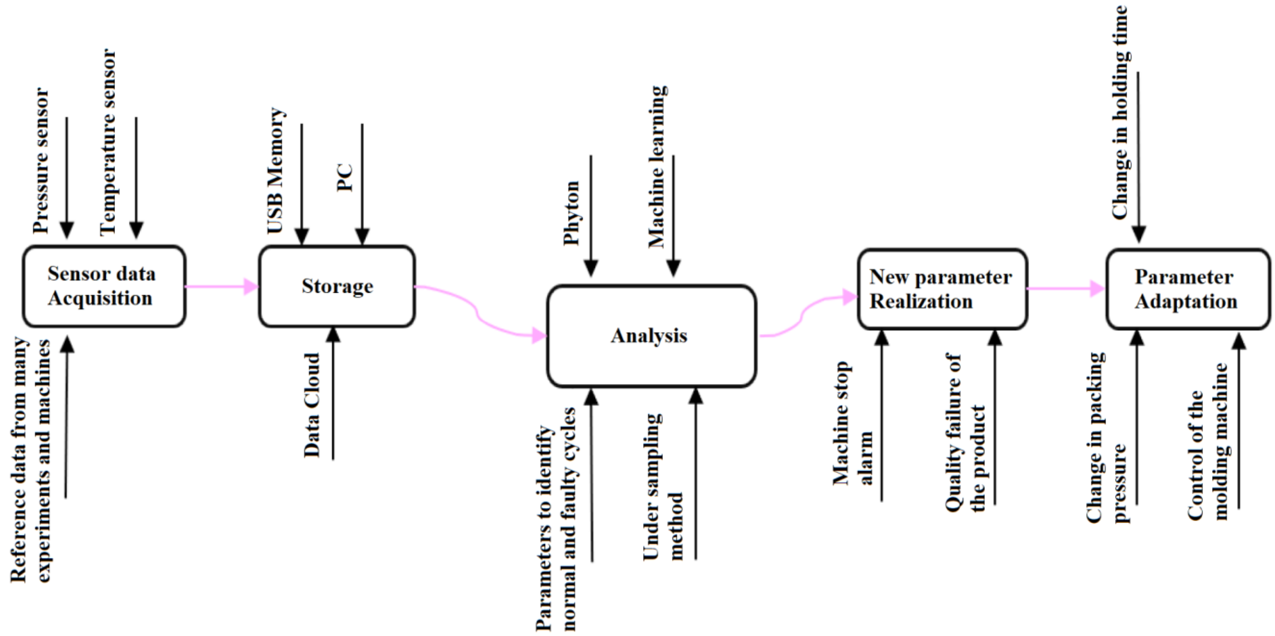


Fig. 8. AI-based smart control system operating principle [12]

Presented methods of the plastic injection moulding quality assurance and the process efficiency improvements shows possible ways to solve problems which occur during the manufacturing. Conformal cooling channels brings considerable benefits to the manufacturing process by improving the quality of the final part and reducing the cycle time by shortening the necessary time for cooling ejected parts. The implementation of conformal cooling requires a new mould design. The AI-based smart control system allows to implement new improvements to the already existing and working system. It lets to increase the quality of the final part and the efficiency of the process by constant monitoring of the input parameters and restoring them when they deviate out of tolerance range.

Since there is another point of view to this topic, the company must consider that ways for testing finished product quality is as vital as the quality assurance in the manufacturing process. The production of the assembly means that the necessary quality assurance reaches a higher and much more challenging level. Sometimes assembly parts are manufactured using the different technology, but in the final result, all components need to fit perfectly together. In this project case, both parts are manufactured using the same technology, which is the plastic injection moulding. In the company X, the quality of moulded parts are checked after producing it by measuring part dimensions. Still, it is not enough to assure the quality of the final product because even if measurements are in the tolerance range that does not mean the part quality will be satisfying. The proper testing is required to ensure that the final product will perform as expected during its exploitation in different environments because the company X sells the product worldwide. The necessity for testing the final product is proven by analysing similar situations. For example, there is a publication which suggests how to test the sealing of the plastic tube properly. It is well presented how the complex test system is created for at first glance, simple product. One end of the plastic tube needs to be closed and hold specific pressures in various working environments. The product must be tested, measuring its performance in all different conditions. The company must check all parameters in advance to avoid facing problems in the future [17].

5. Water meter quality problems

The water meter X is a product which is produced by the company X. It is a water meter with the plastic housing made using the plastic injection moulding manufacturing technology. Since the plastic injection moulding is a very complex process, naturally there are a lot of areas and possibilities for the quality of the final product to go wrong.

5.1. Water meter X manufacturing process

There are few manufacturing processes done simultaneously. The water meter housing, the insert, and the lid are made using the plastic injection moulding. Inside the meter, there are hardware components which are responsible for meter functions and measurements. In the plastic injection moulding department, the company manufactures a few separate parts of the meter. The water meter housing is the base component for the assembly of the final product.

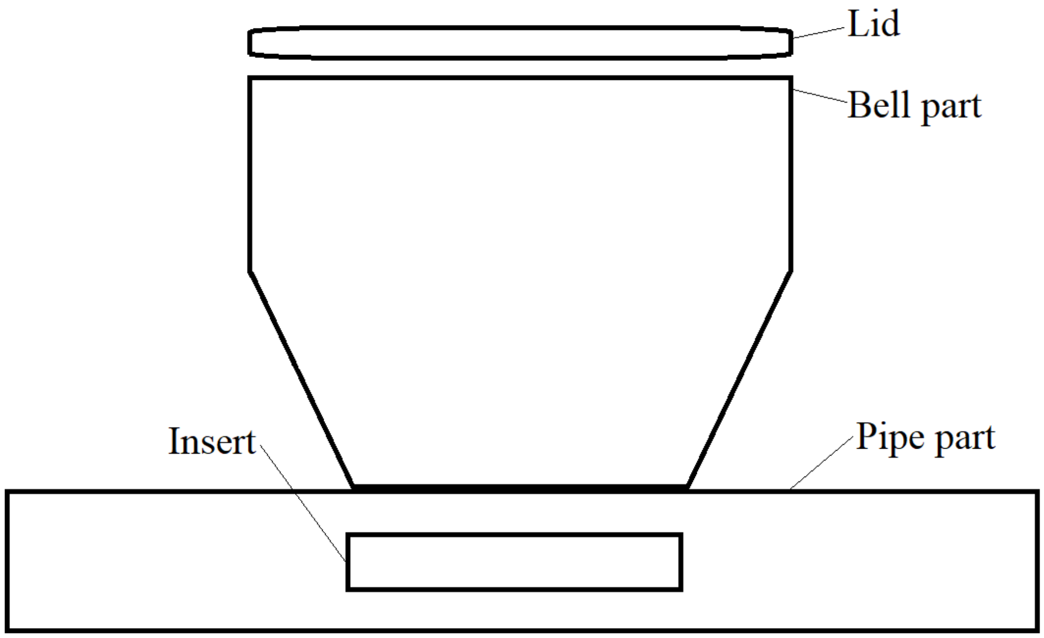


Fig. 9. Scheme of water meter housing components

Concentrating on the water meter body assembly and leaving the installation of hardware components aside, there are three different parts. In figure 9, the sketch of the final product is presented. When put in simple terms, the bottom part is the meter housing, and on top, there is the lid which is glued to the main body. The meter housing is plastic injection moulded as one part. For better understanding, it can be separated into two parts. The pipe through which water flows and the bell in which all hardware components are mounted. There is also one other component which is mounted inside the pipe, and it is called the insert. The insert is an essential part and plays a considerable role in the meter functionality and measurement system.

5.2. Requirements for water meter X housing

The water meter X is a high-quality product which is exported all over the world. The product is used to measure water consumption, and taxes are paid based on its measurements. Naturally, it needs to perform on the highest possible level and be sustainable. It is used not only for the industrial water but also for the drinking water consumption measuring. When the product is used for calculating something that taxes are based on, it needs to go through a lot of different tests and get all sorts of certificates to be acceptable in different regions for different clients. Its materials need to meet hygiene requirements for measuring the drinking water because the material is in contact with it.

The meter also needs to meet the IP68 standard to be waterproof and dustproof. This requirement is applied to all regions. It is essential for installing the meter in challenging environments. For this purpose, there are specific tests that the meter housing must pass to be able to be exploited in extreme environments. It all comes to the injection moulding process because if this process goes wrong or it is not calibrated to meet the final product quality needs, the whole further process of assembly can be faulty. The water meter X geometry has tolerances, but they are very tight. The wrong shape of water meter housing can cause several problems. The lid needs to fit perfectly to meet IP68 standard requirements. Also, the insert which goes inside the pipe, must match and not fall out or get stuck in the middle of the mounting process. The meter housing goes through mounting tests whose purpose is to test body strength. The body strength depends on the plastic injection moulding process. If the moulded part is faulty and has wrong dimensions, some areas of the housing can be too weak to handle required turning, pulling or bending loads.

All requirements for the meter housing are based on its geometry. In the plastic injection moulding process, injection and cooling parameters are playing the biggest role in the result of the meter housing geometry. In the experiment which is done in this project, different injection and cooling parameters were tested to see what impact for the final meter housing geometry it has and how changing different parameters can affect the absolute product quality. Measurements of moulded parts are made to find the best set up of parameters which meats required cycle times and the required level of the quality.

In previously discussed solutions to solve similar problems, articles about the conformal cooling and the usage of artificial intelligence were analysed. These methods and innovative technologies could be used and applied to the water meter X production to increase the quality level, productivity, and production effectiveness. When focusing on the plastic injection moulding process, there are not so many areas to improve, because the mould is already manufactured. Ordering and designing a new mould would be costly and would take a long time to start working with, since lead times in mould manufacturing companies could take months. Same goes for the implementation of artificial intelligence systems in the production. It could bring benefits, but it costs a lot of money, and it is hard to implement. The product, which is used in this experiment requires the research on the selection of the plastic moulding process parameter setup. The results of this experiment will provide the best possible parameter setup which will be used in the future production. After successfully adopting this experimental method for this specific meter, the company will be able to use it for other products much more effectively because the company will know how to perform this experiment.

6. Experimental part

The company produces many different sizes of water meters, and they all have the same bell part with the identical hardware, but different sizes of the pipe and the insert. For this project, the water meter X housing is selected because this variant is sold to countries with extreme environmental conditions.

In this experiment, problematic areas and points of the part must be measured and by using different parameter settings, the best setup must be discovered. There are different parameters affecting the quality of the final product. In the article written by Satadru Kashyap and Dilip Datta process parameter optimisation of plastic injection moulding is discussed. It suggests that parameters influencing the final quality of the part, and the manufacturing process effectiveness can be sorted into three different categories [18].

First, there are injection machine parameters such as barrel, nozzle, coolant temperatures, packing, holding, injection, back pressures, sequence and motion, injection, screw speed, shot volume and cushion. Process parameters which contain mould, melt and cooling temperatures, melt pressure, shear stress, injection, filling, packing, holding, cooling, mould open times, injection, material flow rates, the rate of heat dissipation and cooling and pressure switch over. Finally, there are quality indices such as final dimensions, shrinkage, warpage, sink marks, appearance, and strength at weld lines. There are also cosmetic requirements for burn marks, gate blushes and surface texture.

By taking all these different parameters into mind, the best combination must be discovered to reach the desired quality and cycle times. In the company, there are no smart and innovative measurement systems, so only test and measurement methods based on gathered experience are selected.

6.1. Problem presentation

The problem appeared when the company X received a letter from the company Y (based in a country with extreme environmental conditions) with a claim that the water meter X was found in the field with humidity on the inside part of the screen. This problem was not seen before, so it very quickly became the number one priority to get back faulty meters from the customer to the local facility for the analysis of root causes. It is crucial situation because it raised a lot of questions. First, what percentage of all production meters have this problem. Second, why the problem appeared if the IP68 is checked in the assembly line and all meters are tested inside the vacuum chamber. Right after the company X became aware of this problem, dedicated employees started to fill the 8D report, which is a standard procedure when the claim from the client is received. 8D report is always shared with the client to inform about the progress made on solving the problem. It is essential to note that by the time the company got his complaint, X units were already installed in the field. Besides the 8D problem solving method, company X also has other Lean manufacturing methods implemented in the production. PDCA, MSA, CpK, PFMEA are methods used in different fields and situations of the production. In this case, the 8D report tool suits the situation the best. PDCA (Plan, Do, Check, Act) is used for finding root causes of some specific problems and eliminating them. MSA is the experimental method to measure the number of variations in the measurements process. CpK is used to measure process capability. PFMEA is a process failure mode and effects analysis. It is widely used for identifying possible risks and weak points of any process or operation.

8D report is a customer complains management tool used in a company X when problems related with the provided product occur. It is used to create a controlled flow of dealing with received complain and for solving the situation inside the company. There are eight steps which guide how to deal with a problem most efficiently. It helps to solve the problem much faster. Also, it helps to give the customer a constructive feedback about how the company X is dealing with the problem, what actions are applied, what root causes are found and how the company is making sure that specific situation will not repeat in the future. It helps to keep the customer satisfied and feel more secure with future business with the company X. It gives confidence because the company is showing taken actions transparently and without making false statements or promises [19].

After receiving complaints that some water meters X were found having humidity inside, the company started the problem-solving process with the 8D report. First, the case was created, including simple information shown in the table below. Documentation is needed for tracking the case and for the future to have all information easy to access. It could make the problem-solving process faster if in the future a similar problem is faced in some other country. The basic information is provided in table 1.

Table 1. Basic information about the received complaint

	8D Problem Solving Documentation				
Info	Case title	Humidity inside water meters X			
	Initiator name & company	Company Y			
	RMA number (if applicable)	RMA X			
	Customer Complaint Number	X			
	Company X Part Name	Company X Part Number	Customer Part Number	Production Date/ Serial Number	Quantity Rejected/Returned
	Water meter X	X	X	X	47

D1 is a stage when a team with required competencies and knowledge are gathered and assigned to stay in this team until the problem is completely solved and finished (table 2). Members can be added in further steps if there is a necessity for it. The most important rule is to create this team by thinking of who would be the best fit. It is based on teamwork, so it is important not only to have the required skills but also be able to work together.

Table 2. Building the right team to deal with the complaint

	Establish team	
D1	Name	Function
	X	Quality Engineer
	X	Director of Innovation and Technical Division
	X	Head of R&D quality assurance team
	X	Test technician

The problem description step is the one in which the real work starts. Defining the problem leads to first thoughts on how and where a team will search for possible causes and solutions. Defining the problem is based on the received information. It depends on how much information about the problem is given by the client. If the client provides reports about the problem with specific details, some actions can be taken even before receiving faulty devices in the company. Received information is filled in the D2 part, which is provided in table 3.

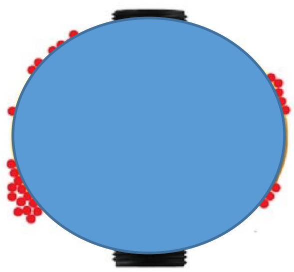
Table 3. Description of a problem

	Define problem
D2	Claim has been received from the company Y that multiple installed water meters have humidity on the inside surface of the screen. The photo included below shows a real example of the problem. All faulty meters received in the company X for further analysis. There is a possibility that more meters can be found with the same problem.
	The sketch or Photo of the problem:
	

The D3 stage is the first action stage where a dedicated team decides if the company needs to stop all already manufactured and prepared products from sending them to the client. The important thing is to understand that containment of all units would be very painful in terms of delivery deadlines, so based on that only 47 faulty units were found from X units already installed, it is only around 0,2% of defective meters. The decision was made not to apply any containment and do the production as before. Of course, it does not mean that the company X is leaving this problem. A team is still working on it but based on a low percentage of faulty meters, the amount is acceptable to replace, because containment would cost much more. There is no D3 table because there is no containment information.

After deciding not to apply any containment as a team is still working on solving this problem, the next step is to find the route cause for humidity inside the meter. The fact that all produced water meters X has IP68 caused worries that testing for the IP68 is not enough when meters are installed and exploited in the extreme environmental conditions. In table 4, the root cause is described.

Table 4. Defining root cause

	Find root cause
D4	A plan for problem-solving meetings, data collection and analysis.
	What was the root cause for the problem?
	Initially, a low percentage of failed devices versus the number of units installed in the field led to a conclusion of accidental manufacturing imperfections, as all meters passed the IP68 test in the assembly line. After receiving and analysing the meters, it was detected that loss of the IP68 happened due to extreme temperature changes in exploitation environment. Significant temperature changes caused the appearance of micro gaps between the bell part and the lid. Temperature changes significantly between 70°C and 20°C because most of the meters are installed on rooftops under the direct sunlight.
	The analysis of leakage points was done for each meter. A graphical representation of each point allows to see pattern of weak spots. It can be observed that most of the weak spots are concentrated at sides of the meter face. 

After inspection of faulty meters, a conclusion was made that the root cause of this problem is the loss of meter tightness because of micro gaps between the bell part and the lid. It happened because of cyclic significant temperature changes. A further step is to explain how this happened and how to make sure that all meters that are sent to the client will not have this problem. Further, corrective actions are provided in table 5. Also, employees with the required skills are assigned to specific tasks.

Table 5. Corrective actions

D5	Define and implement corrective actions	
	Corrective Action:	Who?
	1. A reception of failed meters in the company X for the inspection.	Quality Engineer
	2. Initial evaluation of returned devices. - Visual assessment and measurement of external irregularities; - Planning tests sequence of failed meters;	Head of R&D quality assurance team Test technician
	3. Executing tests: - Non-invasive test in vacuum environment with indicator; - Leakage identification of each meter; - Dismantling of affected devices (a mechanical removal of lids);	Test technician
	4. Report and evaluation of the meter's analysis	Head of R&D quality assurance team
	5. Evaluation report presented to the client	Quality Engineer
	All corrective actions implementation date	

Dealing with this specific case, a quality engineer is a person who is responsible for communication with the client who made this complaint. A quality engineer takes care of answering questions about the company X actions towards this problem, about what root causes of the problem the company found or what is done to make sure this will not happen in the future. In other words, a quality engineer is a person who represents the company during all problem solving and elimination stages. A quality engineer makes and provides reports to the client about the test and analysis results.

A head of research and development quality assurance team is a person who has a big role in this problem-solving process. A quality assurance team does the real work in this situation, which is the inspection of received meters, the analysis of weak points and making assumptions for further direction of the problem-solving process. A research and development quality assurance team can cover all the work from a primary inspection to the elimination of the main root causes of the problem and solving the problem entirely by implementing new process optimisations or applying new testing methods. In this case, a head of research and development quality assurance team is responsible for guiding the team through the process and delegating jobs to different team members. Also, he is taking important decisions regarding what actions the company need to take based on the information gathered from received faulty meters.

A test technician is a member of the research and development quality assurance team who is also the author of this project. A test technician needed to make a primary inspection of received meters and suggest further actions. The experiment of finding the best plastic injection moulding parameter setup and applying further tests was the responsibility of the test technician. One of the main tasks is to provide clear results of performed tests to the head of the team, whether it is good or bad. Based on information given by a test technician, a quality engineer is also providing feedback to the client about the progress made on solving the problem. In table 5, corrective actions and roles of different employees are provided. D5 is a crucial step in the 8D report.

After receiving all meters, a team decided to take lids off and apply measuring of device top bell part dimensions to see if it is in range of tolerances. This client is getting meters only in one size, so all meters are the same. It makes the problem a bit easier to solve since, for now, a team only need to worry about one size. After measuring dimensions, a team saw that most of the faulty meters has dimensions of the top bell part width and length out of the tolerance range. For now, a team need to apply corrective actions and finish filling the 8D report later because further steps are D6 – validate corrective actions, D7 – define and implement preventive actions and D8 – sign off and celebrate. These steps can be finished only when the company can approve that all corrective actions were successful, and the problem was eliminated.

6.2. Current situation

It is essential to understand what the current position of the company is. So, the company X have the client based in a country with extreme environmental conditions which has X units of water meters installed on rooftops with everyday temperature changes between 70°C and 20°C (figure 10). The client found 47 meters during the monthly inspection. The meters had a loss of tightness and humidity on the inside surface of the device screen. The client replaced all faulty meters using additional stock provided by the company X and returned the faulty meters. Right after the reception of the meters, a dedicated team made the first visual inspection and created a visual representation of points through which humidity got inside the meter. Further, a team removed lids and measured the dimensions of the top bell part. The most of the measured dimensions were out of tolerance range, so the conclusion was made that a team need to start from the beginning of the process, which is the plastic injection moulding. Installed meters shown in real-life conditions on the rooftop under direct sunlight (figure 10).

Fig. 10. Water meters installed in the field

After inspecting the work of the plastic injection moulding department, a team found out that they are not assuring the right process. The parameter setup for the moulding process was not calibrated, and it needed recalibration. The idea of the experiment was approved from authorities, and a team decided to set 25 different parameter setups and produce ten units with each setup for the comparison. The important thing is that there are seven critical dimensions that must be kept as close to nominal values as possible.

Dimensions we need to measure takes not only the top bel part width (3) and length (4), but also the length of the meter housing top (2) and bottom (1) pipe part, the diameter of thread part (7), the thickness of first (5) and second (6) sensor zone. The visual representation is shown in figure 11. The lid and the insert part are produced with separate plastic injection moulding tools. It is calibrated to a satisfying level, so the lid and the insert are not taken to this experiment.

Plastic injection moulding parameters a team is changing and applying to different setups are fixed and moving moulding tool sides cooling temperature, holding time, cooling time, holding pressure and the temperature of the injected raw material. After producing 250 different test samples, all of them were measured, and a visual representation of all 25 setups was made making average values for every dimension. Graphs for all seven required dimension changes with each moulding parameter setup shown in the next section. Only tolerance limits of the dimensions are shown in the further work because showing full dimensions is not allowed by the company X.

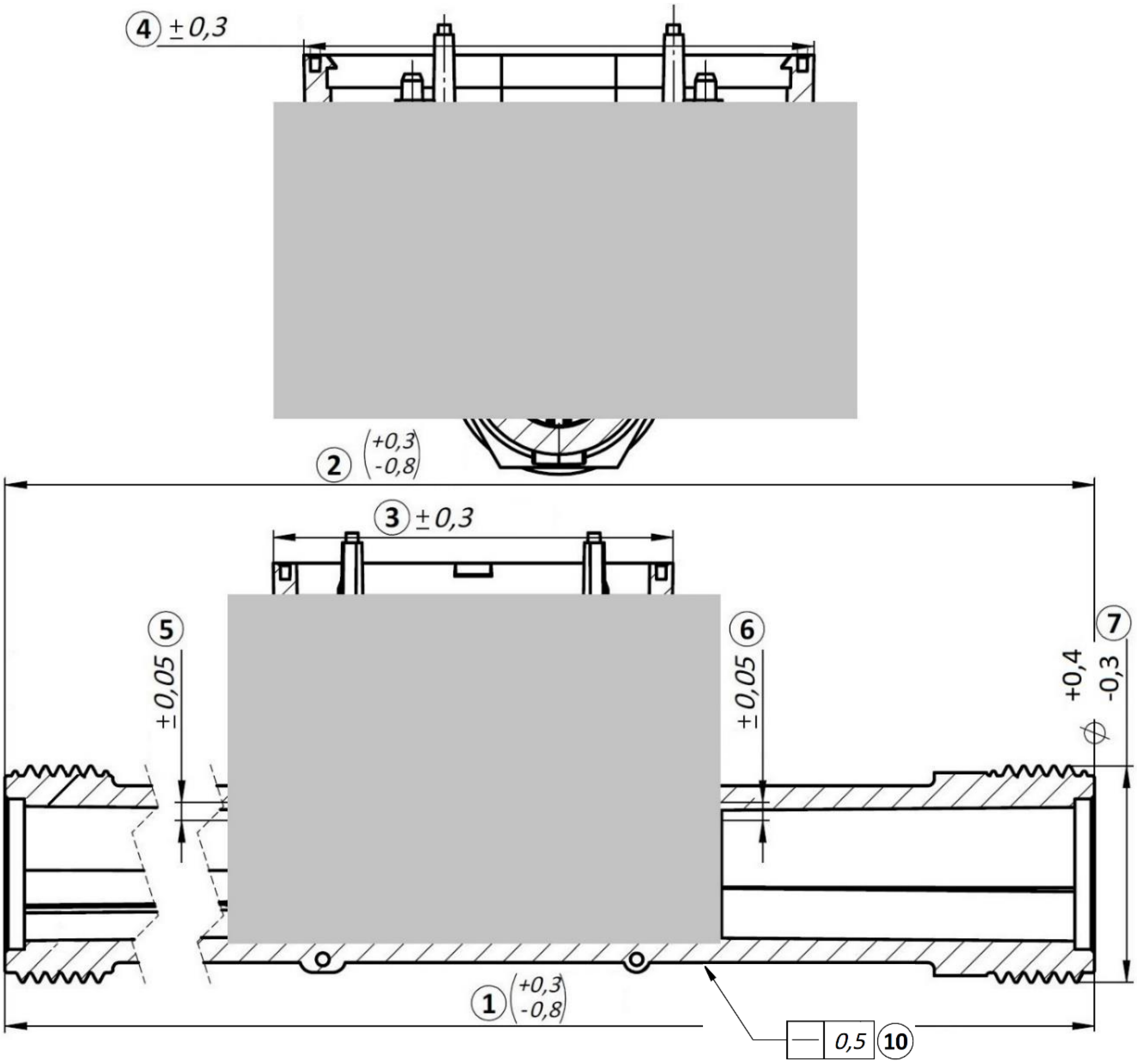


Fig. 11. Water meter X housing dimensions

The mould cooling temperature is responsible for the ejection of the part from the mould. The task was to find the best setup for the mould temperature that it would not take too long to cool the part down. The goal is to find a so-called sweet spot for the mould cooling temperature to eject the part from the mould in the best quality and time ratio. The plastic part shrinks when cooling down so, at a certain point of temperature, it becomes easy to take out of the mould. If that point is passed, the extra time is wasted, because if the part is easy to eject from the mould, it can cool down not interrupting the manufacturing process and keep the cycle time lower. The cooling time has a similar effect, but it is related to how rapidly the part reaches the temperature at which it becomes easy to eject from the mould. This time has a massive influence on the cycle time and being too short, it can cause shrinkage or warpage of the part. The cooling time being too long can lead to excessive mould-in-stresses or possible breakage [20].

The holding pressure and the holding time are the most influential parameters to the part shrinkage. By increasing the holding pressure, it is possible to decrease the part shrinkage to almost none when the holding time to shrinkage curve straightens after reaching a specific amount of time [20]. In this project, the goal is to set and find the best values for these parameters to get the best result of the plastic injection moulding process.

6.3. Comparison of different setup measurements

The produced samples were measured to see the dimension deviation from nominal values. Using 25 different parameter setups 250 sample meters were produced. By finding the average value of every dimension got with each parameter setup, a graphical representation is provided in figures 12 – 18. Each graph shows 25 measurements in the nominal and limit values perspective. Only the tolerance deviation measurements are provided. The pipe part of water meter X housing measured at the top and bottom in order to see if the pipe bending limit (dimension number 10 in figure 11) is in tolerance range.

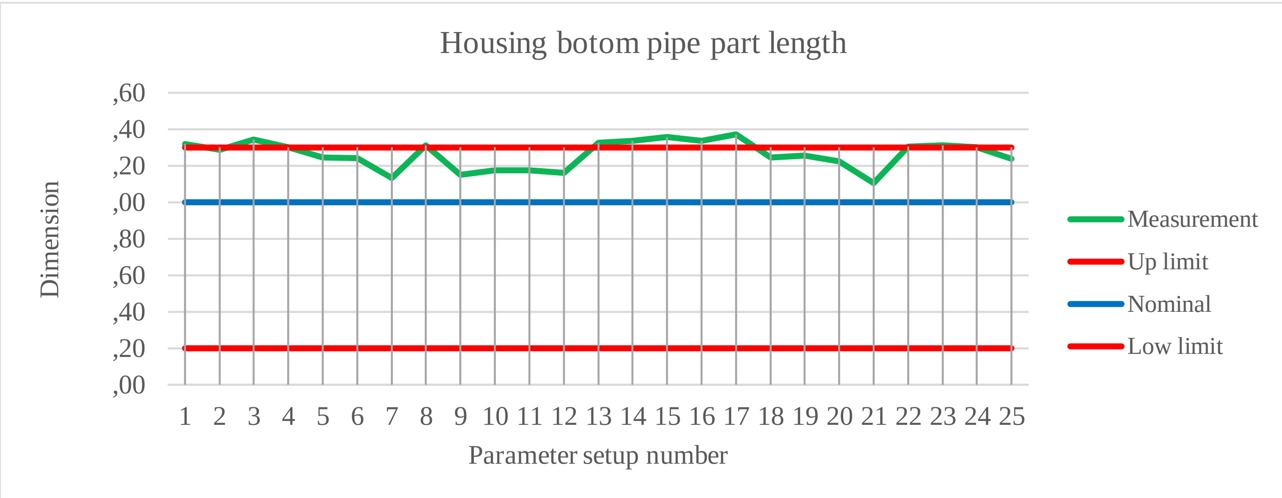


Fig. 12. Dimension number 1

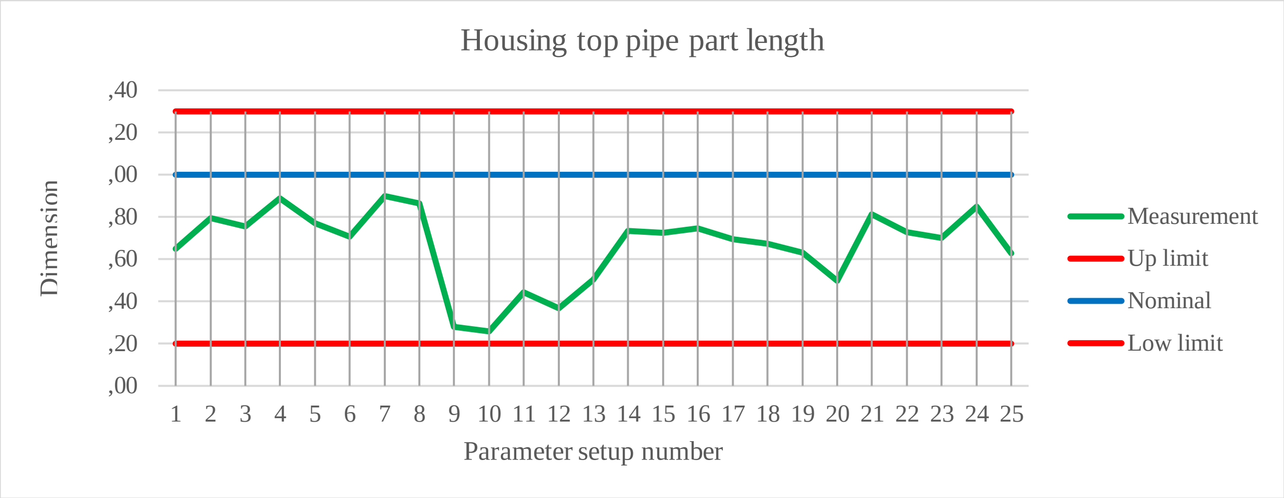


Fig. 13. Dimension number 2

The top bell part width (figure 14) and length (figure 15) are dimensions which has the biggest impact on the water meter X tightness capabilities and quality. These dimensions must be as close to nominal values as possible to assure the desired quality of the meter.

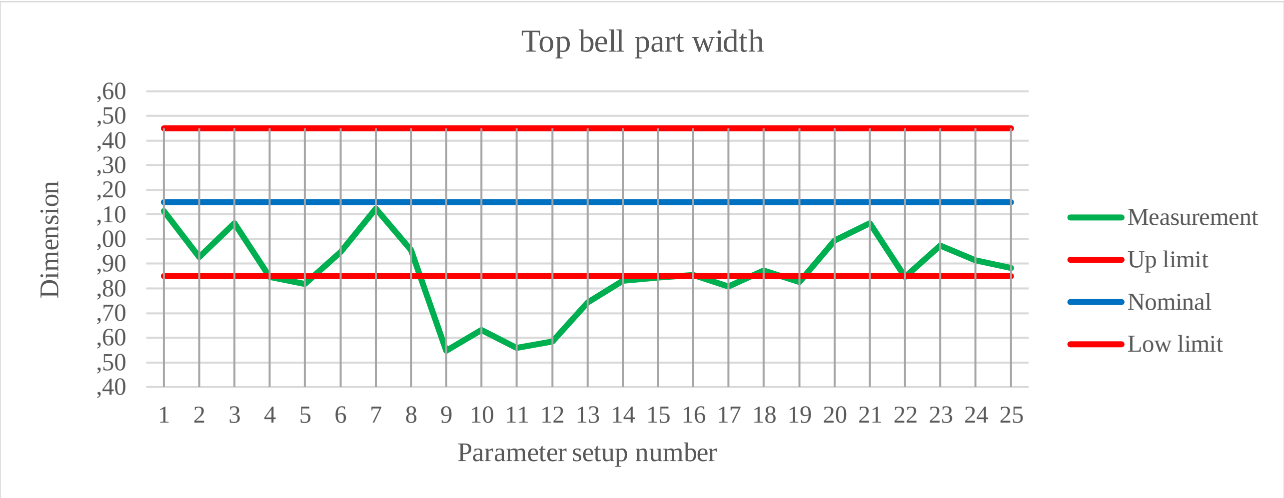


Fig. 14. Dimension number 3

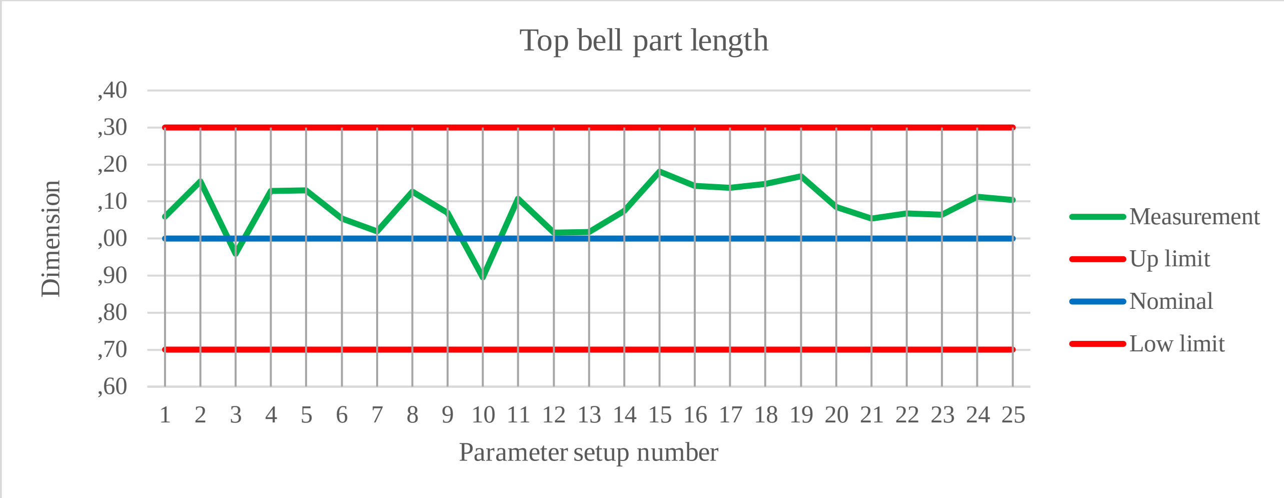


Fig. 15. Dimension number 4

For the first and second sensor part thickness requirement is to have both dimensions similar to each other. The functionality of the meter depends on these points. Dimensions 5 and 6 must be accurate for the correct water meter X water flow measurement performance.

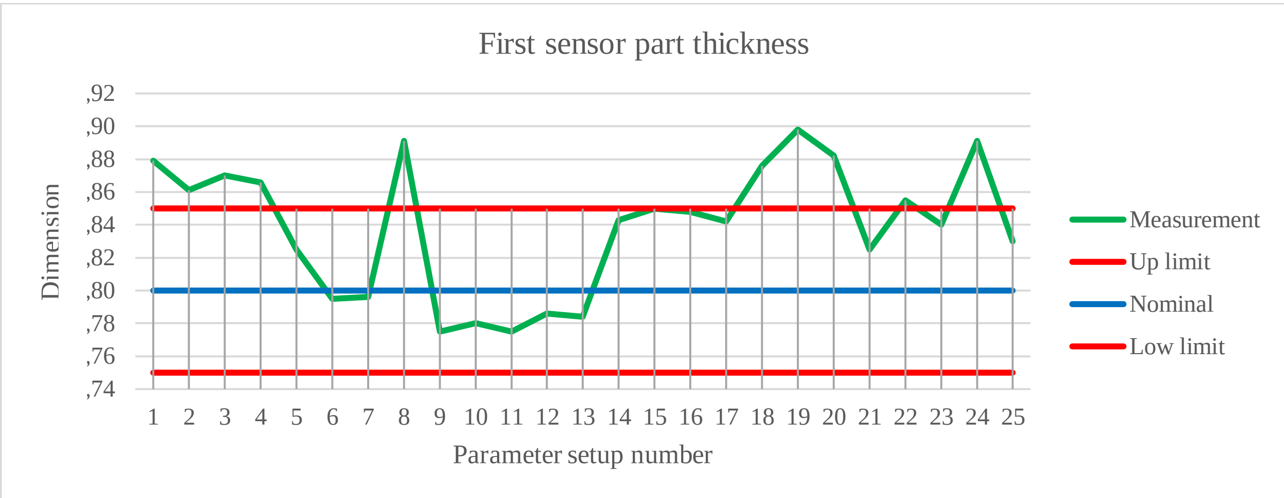


Fig. 16. Dimension number 5

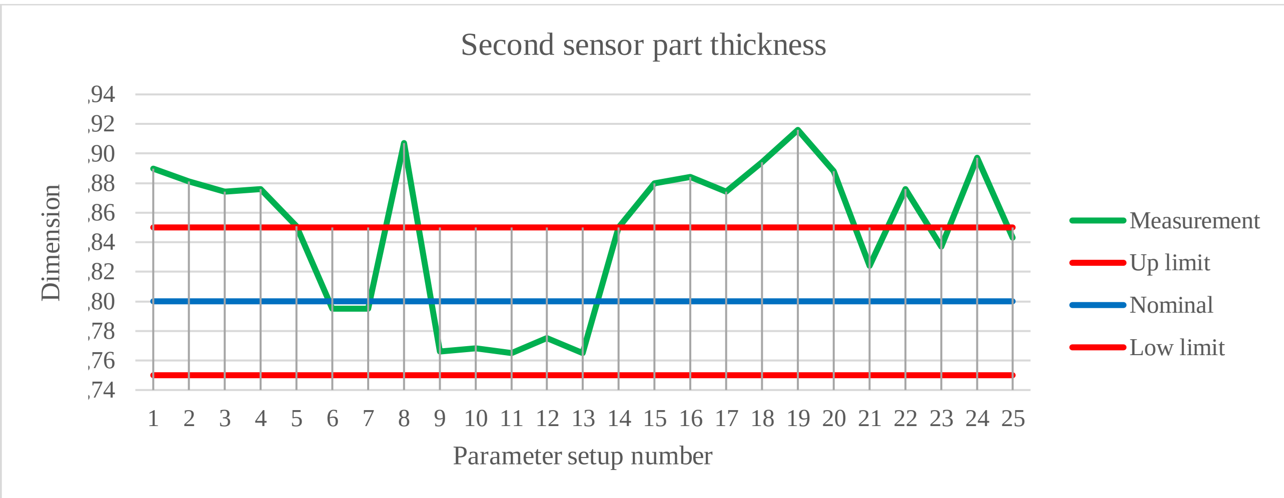


Fig. 17. Dimension number 6

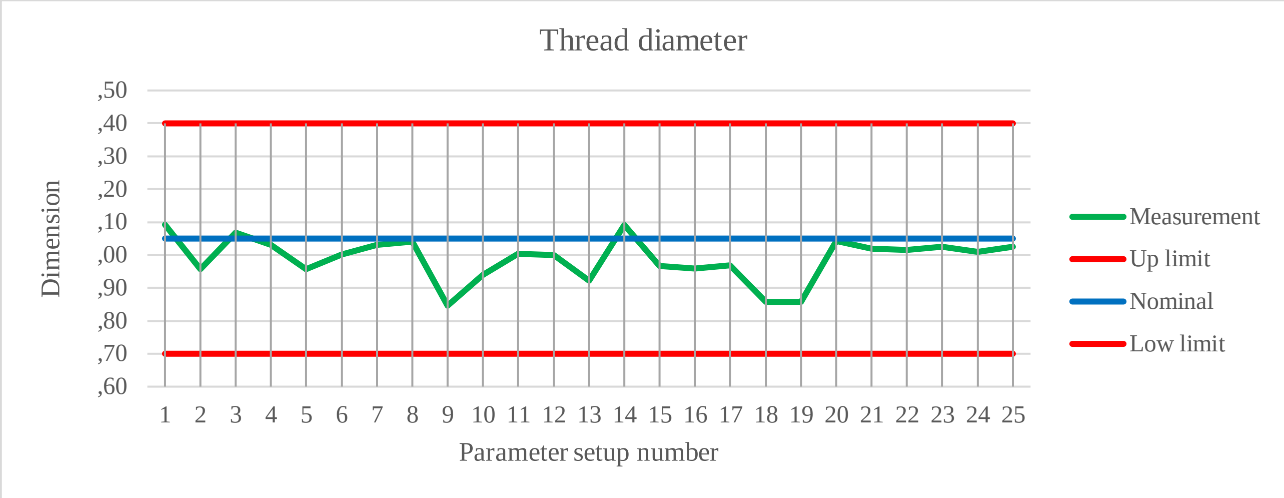


Fig. 18. Dimension number 7

Measurements for points 1, 2, 3, 4 and 7 are made using a precise calliper. It is a standard procedure requiring a basic knowledge. Points 5 and 6 requires much more preparation and time to measure it properly. After measuring all ends with a calliper, the water meter X housing is prepared to be cut in half.

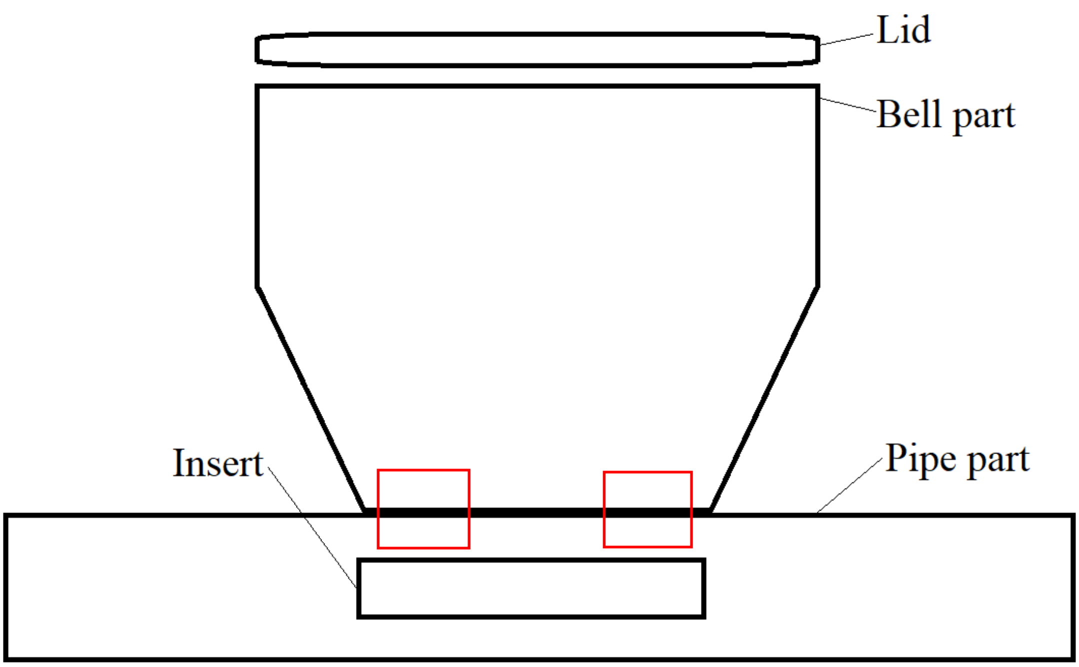


Fig. 19. The view of points 5 and 6

The equipment to measure the thickness of points 5 and 6 (marked red in figure 19) is used. It consists of five different tools. 1 – base plate, 2 – measurement basis, 3 – measuring leg, 4 – holder, 5 – indicator. The system created to measure these points is shown in figure 20. The measuring process view of the meter housing cut in half is presented in figure 21.

Fig. 20. Measuring system for points 5 and 6

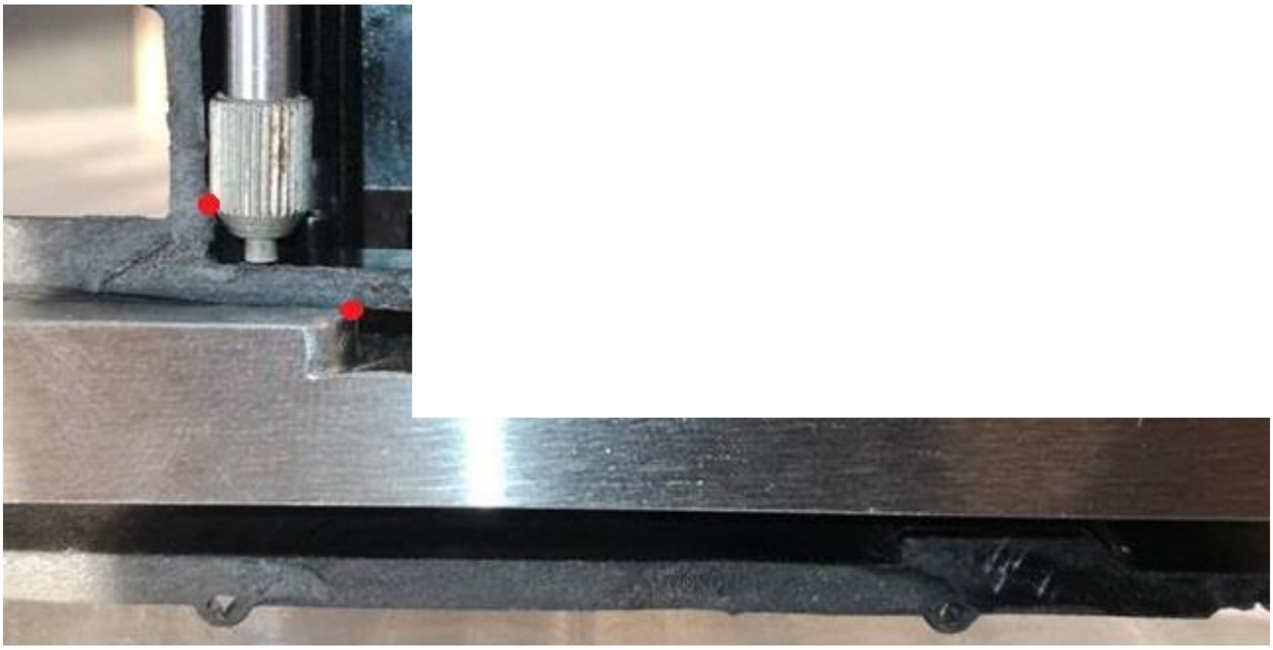


Fig. 21. Measuring process. View of meter cut in half

6.4. Experiment results

Figures 12 – 18 show a graphical view of the measured dimensions deviation. It is clear that changing the injection moulding parameter setup causes significant changes in results. As concentrating on the device tightness problem, a team must make sure that all seven dimensions from figure 11 are correct. Provided graphs are not enough to show the real situation, so ten measurements with each injection moulding parameter setup are taken, and average values are calculated. In total, there were 250 sample units moulded with 25 different parameter setups and 25 average deviations from nominal values for each dimension were calculated. Average tolerance deviation values of all measured water meter housing samples are provided in table 6.

Table 6. Average values from parameter setups

Parameter setup nr.	Housing bottom pipe part length, mm	Housing top pipe part length, mm	Top bell part width, mm	Top bell part length, mm	First sensor part thickness, mm	Second sensor part thickness, mm	Thread diameter, mm
1	+0,3190	-0,3510	-0,0360	+0,0590	+0,0790	+0,0900	+0,0420
2	+0,2890	-0,2070	-0,2230	+0,1540	+0,0610	+0,0810	-0,0930
3	+0,3420	-0,2440	-0,0850	-0,0420	+0,0700	+0,0740	+0,0180
4	+0,3020	-0,1110	-0,3030	+0,1280	+0,0660	+0,0760	-0,0200
5	+0,2470	-0,2310	-0,3310	+0,1300	+0,0250	+0,0510	-0,0930
6	+0,2430	-0,2940	-0,2010	+0,0540	-0,0050	-0,0050	-0,0490
7	+0,1330	-0,1010	-0,0260	+0,0202	-0,0040	-0,0050	-0,0190
8	+0,3120	-0,1350	-0,1940	+0,1260	+0,0910	+0,1070	-0,0090
9	+0,1520	-0,7200	-0,6030	+0,0700	-0,0250	-0,0340	-0,2040
10	+0,1750	-0,7420	-0,5190	-0,1050	-0,0200	-0,0320	-0,1110
11	+0,1750	-0,5580	-0,5910	+0,1070	-0,0250	-0,0350	-0,0470
12	+0,1600	-0,6330	-0,5660	+0,0160	-0,0140	-0,0250	-0,0500
13	+0,3250	-0,4970	-0,4060	+0,0180	-0,0160	-0,0350	-0,1280
14	+0,3360	-0,2650	-0,3190	+0,0750	+0,0430	+0,0500	0,0410
15	+0,3590	-0,2760	-0,3060	+0,1810	+0,0500	+0,0800	-0,0830
16	+0,3370	-0,2540	-0,2960	+0,1420	+0,0480	+0,0840	-0,0920
17	+0,3720	-0,3050	-0,3430	+0,1370	+0,0420	+0,0740	-0,0820
18	+0,2440	-0,3270	-0,2770	+0,1470	+0,0760	+0,0940	-0,1920
19	+0,2560	-0,3680	-0,3240	+0,1680	+0,0980	+0,1160	-0,1930
20	+0,2250	-0,5010	-0,1560	+0,0850	+0,0820	+0,0880	-0,0070
21	+0,1050	-0,1880	-0,0840	+0,0540	+0,0250	+0,0240	-0,0300
22	+0,3060	-0,2710	-0,3040	+0,0680	+0,0550	+0,0760	-0,0340
23	+0,3120	-0,2980	-0,1750	+0,0650	+0,0400	+0,0370	-0,0240
24	+0,3000	-0,1510	-0,2360	+0,1130	+0,0910	+0,0970	-0,0410
25	+0,2370	-0,3710	-0,2680	+0,1050	+0,0300	+0,0430	-0,0240

From the table above, it is clear that compared with each other, just two injection moulding parameter setups are worth the further look. By extracting 7th and 21st setups, it can be compared once again between each another. In the table below, the parameter setup number 7 is the best option and entirely acceptable for production. In setup number 21, only one dimension is better, but the rest values are closer to the nominal in the parameter setup number 7. The parameter setup number 9 is shown in table 7 for comparison. This setup is the worst of all 25. The width of the top bell part is way out of tolerance range, making this setup impossible to use. Only one wrong dimension could cause further problems in the water meter X assembly process.

Table 7. 7th, 9th and 21st parameter setups

	Housing bottom pipe part length, mm	Housing top pipe part length, mm	Top bell part width, mm	Top bell part length, mm	First sensor part thickness, mm	Second sensor part thickness, mm	Thread diameter, mm
Tolerance range, mm	+0,3 -0,8	+0,3 -0,8	±0,3	±0,3	±0,05	±0,05	+0,4 -0,3
Nr 7, mm	+0,1330	-0,1010	-0,0260	+0,0202	-0,0040	-0,0050	-0,0190
Nr 21, mm	+0,1050	-0,1880	-0,0840	+0,0540	+0,0250	+0,0240	-0,0300
Nr 9, mm	+0,1520	-0,7200	-0,6030	+0,0700	-0,0250	-0,0340	-0,2040

In figure 11, there is one additional requirement which is applied for the pipe part of the water meter X. The condition is that straightness of the pipe part must not go ±0,5mm (10) away from a straight line. To check if this requirement is fulfilled, the top and bottom deviation of pipe length measurement must be added to see which one is better. So, for the 7th parameter setup deviation is 0,2340mm, and for the 21st setup it is 0,2930mm. The parameter setup number 9 deviation of pipe straightness is out of tolerance range with a value of 0,8720mm. Again, the 7th setup is the one to apply in production. Bellow, the 7th parameter setup is shown in table 8.

Table 8. 7th injection moulding process parameter setup

Fixed mould side cooling temperature (°C)	130
Moving mould side cooling temperature (°C)	145
Holding time (s)	5
Cooling time (s)	45
Holding pressure (bar)	65
Raw material injection temperature (°C)	355

Plastic injection moulding parameters shown in the table above are changed in every different setup used for the experiment. This decision was made based on the influence level to the final part geometry. All parameters, including selected ones and ones which was not mentioned in the experiment, was calibrated to reach water meter X housing dimensions as close to nominal values as possible. In the preparation stage of the experiment, it was found that the parameters selected for this work are the most influential to the final part quality and dimensions. Otherwise, if more parameters would be taken into consideration, the experiment would become much bigger and hard to control. It was better to select specific parameters for the analysis, which are easy to handle and allows reaching satisfying results. Parameters which had the most influence on the geometry of the final part was the holding time and holding pressure.

6.5. Applying testing

Since a team managed to improve the plastic injection moulding process and found the best setup for moulding parameters, the further step is to apply the testing method to assure tightness of the assembled water meter X housing. After producing 50 test samples using the best-found moulding parameter setup, a testing solution using the vacuum is developed. This testing method is simple regarding the needed equipment and preparations. It is based on placing the meter inside the chamber with a negative pressure. Similarly, as points 5 and 6 were measured in the previous stage of this project, the same indicator is used on the meter lid to track its deformation.

Fig. 22. Placing meter inside the vacuum chamber

When the meter is placed inside the vacuum chamber (figure 22), the rest of the system allows to control air pressure using the valve with a pressure indicator. With air pump, the air inside the chamber is sucked out to reach a pressure of -0,5bar. Since the meter has higher pressure inside, it starts to deform. The lid is the area on the device which has the lowest thickness, and after putting the meter housing in this environment, it starts to deform. Selected pressure is -0,5bar because when applying tremendous pressure, the meter can lose its shape and break at some point. The equipment used to perform testing is shown in figure 23.

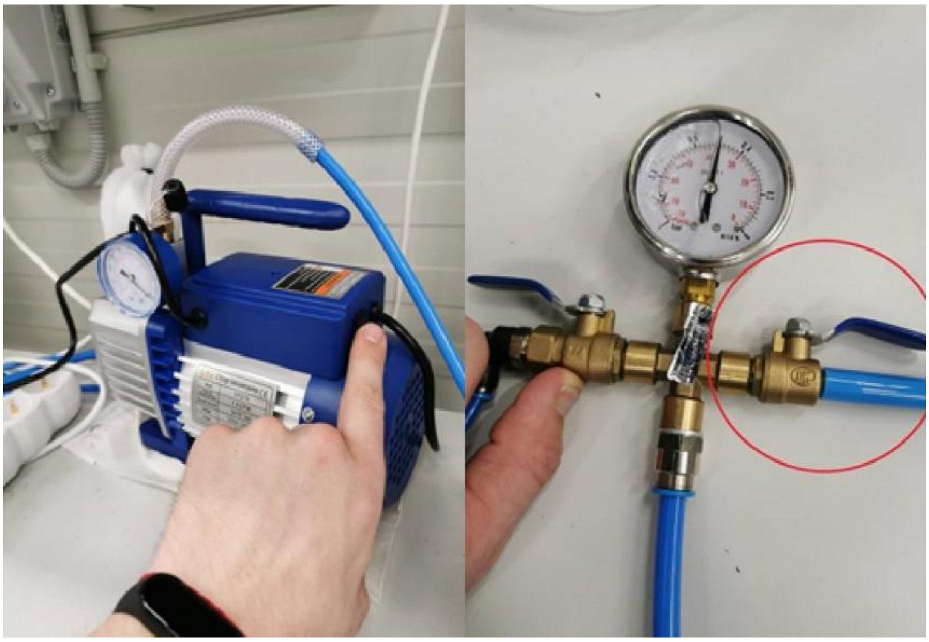


Fig. 23. Air pump and valve with pressure indicator

Figure 24 shows that when the -0,5bar air pressure environment is created inside the chamber, the meter starts to deform. The goal of this test is to keep the meter in these conditions for 60 seconds. If the lid keeps the same amount of deformation for 60 seconds and does not start to go back to its original shape, it can be said that this test is passed, and the result is positive. This test was applied for all 50 samples, and all of them passed the test.

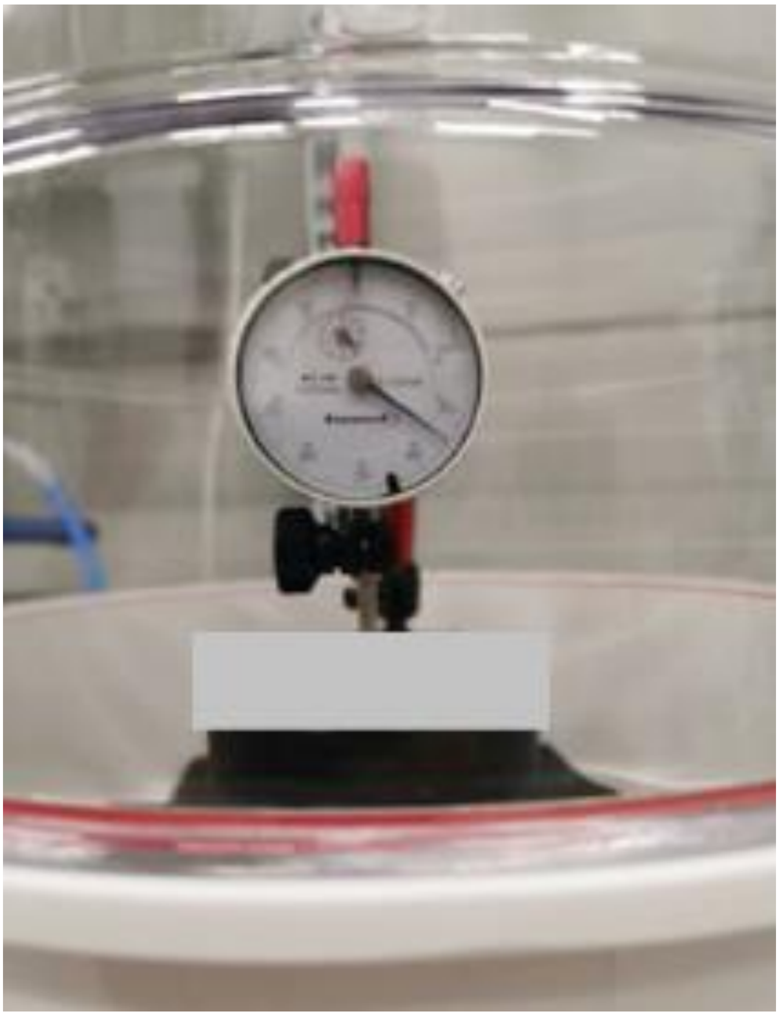


Fig. 24. Meter lid deformation in vacuum

The performed testing method using the vacuum chamber shows positive results gained by improving the plastic injection moulding process. The discussion on further required actions began by raising a question if the vacuum chamber testing method assures the desired quality of the product.

7. Solution of the problem

The water meter X housing problem seems to be solved because all assembled meters with newly moulded plastic housings passed the vacuum test. During the meeting with other team members dedicated to solving this problem, which is humidity inside the water meter X, the discussion if the parameter selection improvement in plastic injection moulding process is enough to call this problem solved completely. The client who made a complaint about this problem is one of many clients based in countries with extreme environmental conditions. It is essential to maintain a relationship in the highest possible level because when the client finds these faulty meters already installed in the field, it causes trouble to replace meters and send them back to the company X for inspection. The way to assure that all meters which are leaving the factory and going to the client will be perfect quality and will not fail to perform during their exploitation must be found. Guaranteeing the ideal quality of the meter will eliminate negative influence in the company business relationship and improve chances of doing business with the same client in the future.

The solution of this problem must guarantee that none of the meters will need replacement because of humidity signs inside them. The client should feel safe and trust the company X on provided products. Finding faulty meters creates doubts about quality and brings questions such as how many more faulty meters are installed and how the problem is being solved in the company X factory to make sure that it will not happen again in the future. The company must provide a testing method that restores confidence which the client had on our product. The only way to reach that is to recreate extreme environmental conditions that the meter faces in real life. Since all meters are installed on the rooftops, the temperature rises significantly during the day and drops down at night. The actual view of how devices are installed is shown in figure 9. Since the problem occurred because of these significant temperature changes, the decision was made to simulate these conditions in the company X factory. If the meters would be tested for a specific amount of cycles, and all of them would pass this test, the company could say that it will stay the same and quality will not dropdown.

The idea for this test method is taken from the IP65 standard, which is water jets. The water meter X passes the IP68 standard requirements easily, and its testing is agreed between the client and the manufacturer. The IP65 standard is not required at all, but the idea is suitable to implement for the humidity problem testing. Specific aspects of the IP65 testing are taken and customized to meet the company X needs, which is only the idea of the method. It states that water projected by the 6,3mm diameter nozzle against the enclosure from any direction shall have no harmful effects to the tested device. The water jets testing requires the specific pressure (0,3bar) of water sprayed on tested devices from a 3 meters distance. Tested devices are considered good quality if they can survive these conditions for 3 minutes. In the company X case, these requirements are not relevant because only the idea of the method is used [21].

This test method does not need to be approved by any official standards or requirements. The only thing which must be reached with this test method is to assure that all meters leaving the factory are the best quality and will not lose their tightness and stay hermetic in extreme environmental conditions. The same 50 meters which passed the vacuum testing are selected for the further work. The purpose of this test is to check the samples susceptibility to severe climatic exposures – simulating the hot and humid environment changing rapidly to cool stormy rain conditions multiple times. Testing conditions are provided in table 9.

Table 9. Rain testing conditions

Ambient conditions:	
Air pressure	960mbar ÷ 1 060mbar
Relative humidity (RH)	25% ÷ 75%
Room temperature	+23ºC ±5ºC
Test profile conditions:	
Meter position	Random
Hot period temperature	+70°C
Cold period temperature	+20ºC
Hot period duration	45min
Cold period duration	45min
Transition duration	15min
Rain simulation	1h (during "cold period")
Number of test cycles	10

In table 9, testing conditions are provided alongside ambient conditions of the room where testing is performed. The goal is to speed up the real-life process of the meter facing day and night conditions by changing the temperature environment ten times in the same periods. Rain is applied to the process because for meters to suck the humidity inside, they must not be placed underwater but covered with water instead. This process replicates the rain in real life. Applying the rain only when the temperature is going down is needed because in cooling period meters start to suck water inside through micro gaps caused by the wrong plastic injection moulding process parameter setup. In figure 25, one test cycle is shown together with the temperature change and period when the rain effect is applied.

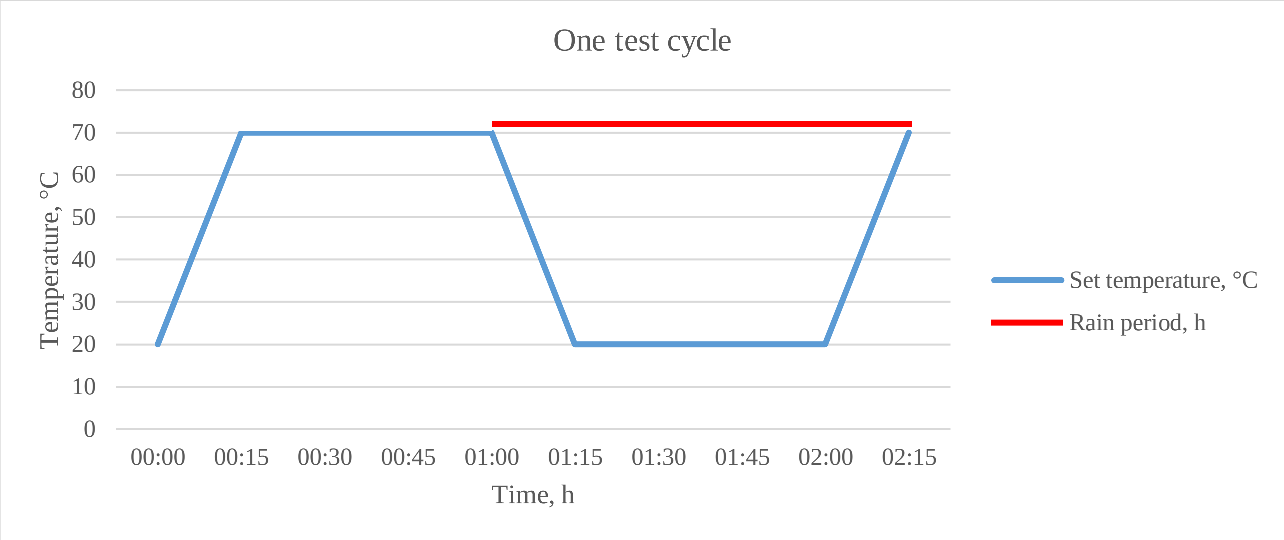


Fig. 25. Rain testing one cycle representation

For this test method, the 300L Temperature humidity test chamber "Yuanyao" is used which is shown in figure 26. All meters are placed in random positions just to be able to fit more inside. In figures 26 and 27 views of placed tested meters are provided during the water spraying process. This chamber is capable of changing the temperature form 20°C to 70°C in 15 minutes and keeping it stable for 45 minutes. The chamber is hermetic, so it allows to apply water spraying inside it from the top to cover all of the meters. Water goes down the drain, and with the help of a water pump, it is resprayed on the meters. The rain effect is repeated during the cold temperature period. During the hot period, water is not applied on the meters.

Fig. 26. 300L Temperature humidity test chamber “Yuanyao”

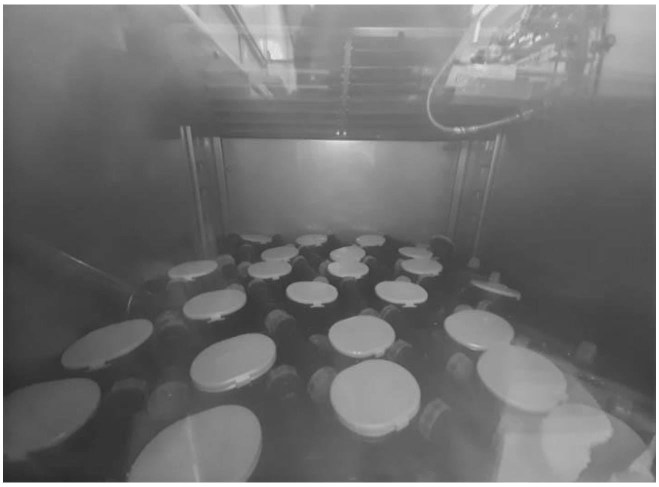


Fig. 27. Water spraying process

After ten cycles, a team still found one faulty meter with humidity signs on the inside part of the device screen, which is 2% of the total tested quantity. The additional action which allowed be sure that the method works correctly was taken. Older meter housings were gathered and put in the same conditions for ten cycles. The inspection showed that 6 out of 50 meters (16%) has a humidity inside. The significant improvements are apparent, but there is a negative side to that. It is hard to tell the exact number, but there is a big chance that the 2% of already installed meters have this problem, and it will appear eventually. Of course, meters will be replaced, but it is essential is to make sure that this problem is solved completely. Unfortunately, based on test results, it is clear that the problem was not eliminated by improving the plastic injection moulding process. The result of this experiment is clear. A massive improvement in the quality of devices was made regarding working in extreme environmental conditions, but all the root causes of this problem was not found. Since a reliable testing solution was created, now a team can make sure that all devices leaving the factory are capable of working in drastic temperature changes and a humid environment. With these results, another issue appears. In order to assure the desired quality of the meters, all produced meters must be tested. The current equipment is not capable of doing that. "Yuanyao" chamber is too small, and with doing testing for ten cycles, there is no chance that it will check all meters in time. It would take too much time, and with strict demand and manufacturing time requirements, it is not possible to extend the manufacturing time by that much. It would create a bottleneck effect on this testing stage. Method is excellent and reliable, so the next step should be creating a new system which would be capable of fitting at least 1 000 meters in one batch. It would be fast enough to go together with the production at the same speed. It would add one more stage to the manufacturing process, but considering the importance of solving this problem, it must be implemented to the production. While producing meters with the additional rain testing stage, a team will be able to search for other root causes of the meter problem being not hermetic. If other root causes would be eliminated successfully in the future, the rain test could be taken off the manufacturing process.

7.1. Rain testing improvement

The decision was made that the rain chamber testing is the quality-assuring problem solution which can be applied right away. The problem is that when the rain testing procedure is added to the production, a so-called bottleneck situation appears. Manufacturing capacity is roughly 1 000 water meters per day. One test cycle currently takes two hours. Since ten testing cycles must be done, there is a need of 20 hours to finish the testing stage, and the maximum number of meters that can fit in one testing batch is around two hundred. There is no way all of the meters can be tested using current equipment.

In figure 27, the principal scheme of possible rain test bench is provided. It is a suggestion of how the bottleneck effect could be solved by merely increasing the number of tested meters. Currently, the temperature and humidity test chamber is used, which can control the temperature itself. For this new test bench, such test chamber will not be used. Instead, a testing chamber with temperature-controlled only by using water could be developed. It is possible to heat up and cool down water in the same cycle times as in temperature and humidity test chamber. Eight shelves could be placed inside the test chamber. One meter takes 0,0045m^2 of space. If one shelf is 0,65m^2 in total, there is 5,2 m^2. That means the chamber could easily fit 1 000 meters inside. All meters could be placed horizontally. If would cover one-day manufacturing capacity and bottleneck effect would be eliminated.

Now in the temperature and humidity test chamber, the water from the water supply system is used, and since it is not clean enough, one additional step is needed, which is cleaning the meters. This happens because the water from the water supply system leaves watermarks on meters, and it is not acceptable. Meters must be clean and ready for packing. To have clean meters after the testing procedure, the distilled water must be used, which will not leave any watermarks. During the testing with this testing method, meters are always covered with water inside the chamber. The problem is that after testing, the meters must be dried to be able to pack. In a new test bench, the drying system could be implemented which could use two positive temperature coefficient air heaters and two ventilators to create the hot air ventilation system. The structure would be able to dry meters entirely in four hours. That makes the testing cycle 24 hours long, including ten testing cycles, and drying procedure. With 1 000 meters, the 24-hour testing period would be acceptable.

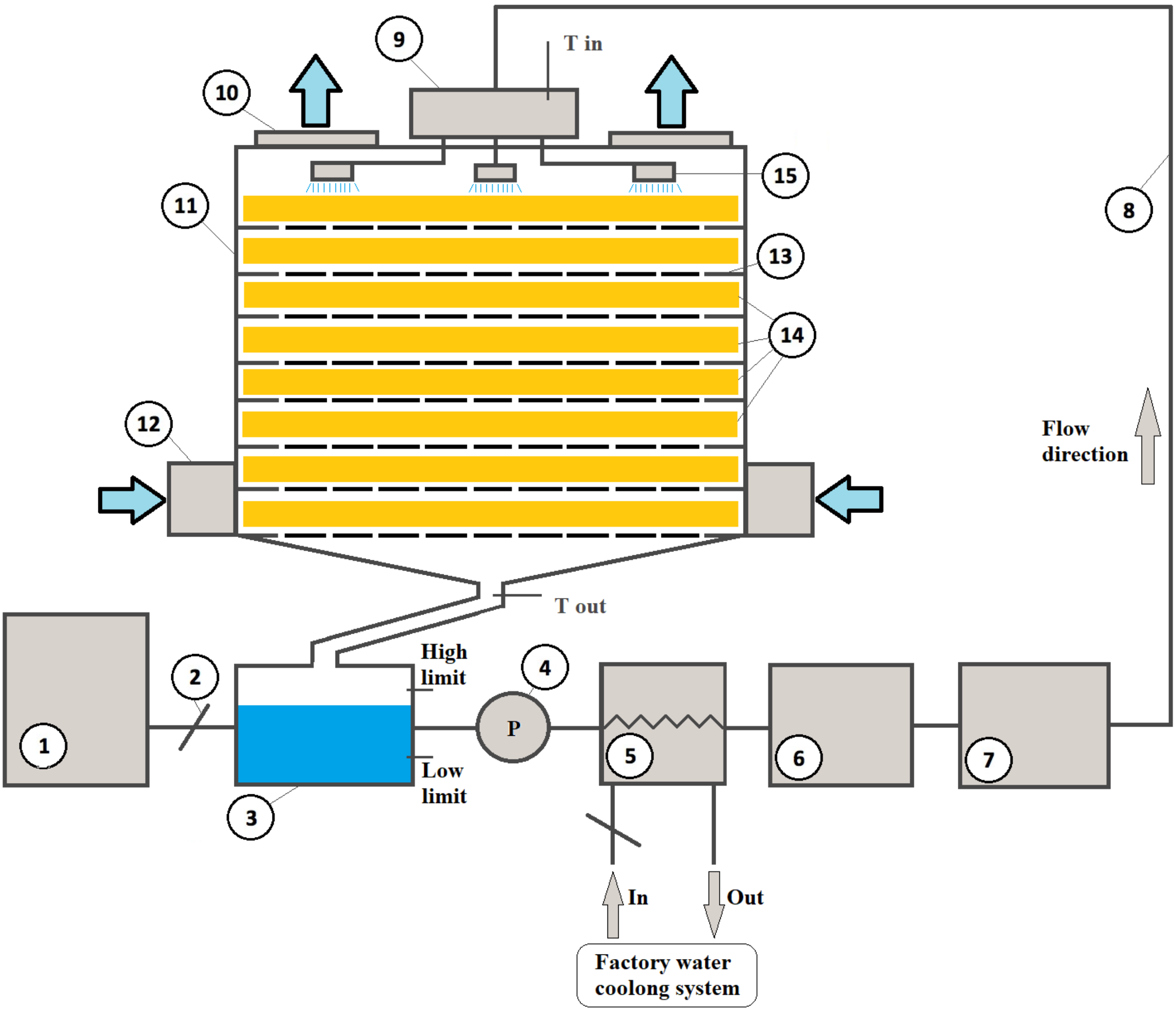


Fig. 28. Rain test bench principal scheme

In figure 28, all components of the new rain test bench are shown. The principal scheme shows how test bench works. The water cycle starts from the water tank (3), which has the high and low limit indications and the low limit sensor. The low limit sensor controls the valve (2), which is turned on when the water level inside the tank drops below a low limit. It is worth to mention that this procedure is done only once in between the testing. Otherwise keeping the tank constantly topped up would cause the tank to overfill when a test is stopped (when the accumulated water drains back from the chamber). When batch of meters is changed to a new one, the water tank is filled from the distilled water tank (1) automatically. The water distillation apparatus can produce 2 litres per hour, so since the cycle of spraying water is 20 hours, it can fill its 20 litres capacity to full in time. During the 20 hours of spraying water, valve (2) stays shut. A water flow direction is shown in the scheme. A water pump (4) reaches the flow speed of $2m^3/h$. All components are connected with a pipe (8) which is one inch in diameter. After a water pump, there is a water to water heat exchanger (5) which is connected to the factory water cooling system. During the hot and cold cycles, it is used to change the water temperature. During the hot cycle, the valve is closed, and the water is heated up. During the cold cycle, a valve is open, so the cold water from the cooling system could access a water heat exchanger (5). Inside the heat exchanger (5) there is a stainless-steel plate through which cold water temperature is transferred to the water in the system. The water temperature in the system is decreased by touching the cold stainless-steel plate. Since there are only 15 minutes each cycle to heat water to 70°C and cool it down to 20°C, there is a need for additional components. To heat the water faster, there is a 12kW instantaneous water heater (6) and a 20kW air to water cooler (7). To reduce the temperature from 70°C to 20°C, only use water from the cooling system is used, which is 10°C. After these components, the water reaches collector (9), which distributes the water into a water spraying nozzles (15). Water meters marked yellow (14) are placed inside the chamber (11). The shelves (13) for placing meters are made from stainless-steel net with empty gaps for the water to go down. All of the sprayed water reaches the water tank (3) and starts a new cycle. The water distillation apparatus is needed because during the process of the 20-hour temperature cycles water evaporates, thus making the concentration of naturally melted salts in the water to go up and leave sediments on the meter plastic housing. That is why the filling of the water tank (3) with distilled water after each ten temperature cycles is needed. After 20 hours of keeping meters covered with water in a changing temperature environment, they must be dried up. It is done using two electric 2kW PTC heaters (12) and two suction fans on the top (10). PTC heaters apply the heat to the air flowing to the chamber and fans suck the air out. The direction of the airflow is indicated with arrows. This system assures a constant air recuperation changing the humid air with dry, hot air. It helps to dry up water meters entirely in four hours and makes them ready for the immediate packing.

Table 10. Components for new rain test chamber

2	Salenoid valve SCG238 046 - 21HT4K0Y160 [22]
4	Water pump Speroni RSM 5, 1,4kW [23]
5	W–W heat exchanger ZC250HP-10P [24]
6	Instantaneous water heater Kospel PPH2-9 12kW [25]
7	Water cooler RS20 20kW Neoair [26]
8	Pipe Heizko, Ø26mm [27]
9	Water collector [28]
10	Suction fan Haushalt 150X1 [29]
12	Electric 2kW PTC heater B2 [30]

In table 10, all components that would need to be bought are listed. The selection of components dedicated for heating the water is made by using the calculation of heat energy Q (J). The equation consists of mass m (kg), specific heat c (J/kg·K), and temperature change ΔT (°C). In this case mass of 1 000 water meters is 400kg, specific heat of water meter material is 2 500J/kg·K, and ΔT is 50°C. In equation 7.1.1, needed heat energy to maintain the required temperature of water in the system is calculated. Based on the calculated result, instantaneous water cooler is selected, which actual power output is higher than needed just to be sure it is enough. Other components are set accordingly.

$$Q = mc\Delta T \tag{7.1.1}$$

$$Q = (1000 \cdot 0{,}4) \cdot 2500 \cdot 50 = 14kWh$$

In the factory, there is a water-cooling system which can easily be applied to this rain testing and water distillation apparatus which company owns for other purposes but uses not that often. The water distillation apparatus is powerful enough to fulfil testing needs. In a table, piping and the whole construction of the frame is not provided because it will need to be done separately. The entire system must be designed first to decide what parts will be required to order for the assembly. In figure 29, purposed main frame of the test bench is shown together with stainless steel shelves installed. All components would fit on the top and bottom space of the frame making the whole test bench very easy to move and compact to store. On the bottom of the frame, there will be a set of wheels for the effortless movement requiring only 0,9 square meters of the floor space. When in use, it would only need to connect to the factory water cooling system and the water distillation apparatus. All other parts and components would be fixed to the frame, making it the assembled structure. The sketch for the frame is primary, showing just the idea of how the assembly could be solved. A visual representation is good for generating assembly ideas and imagining how all parts and components could be installed.

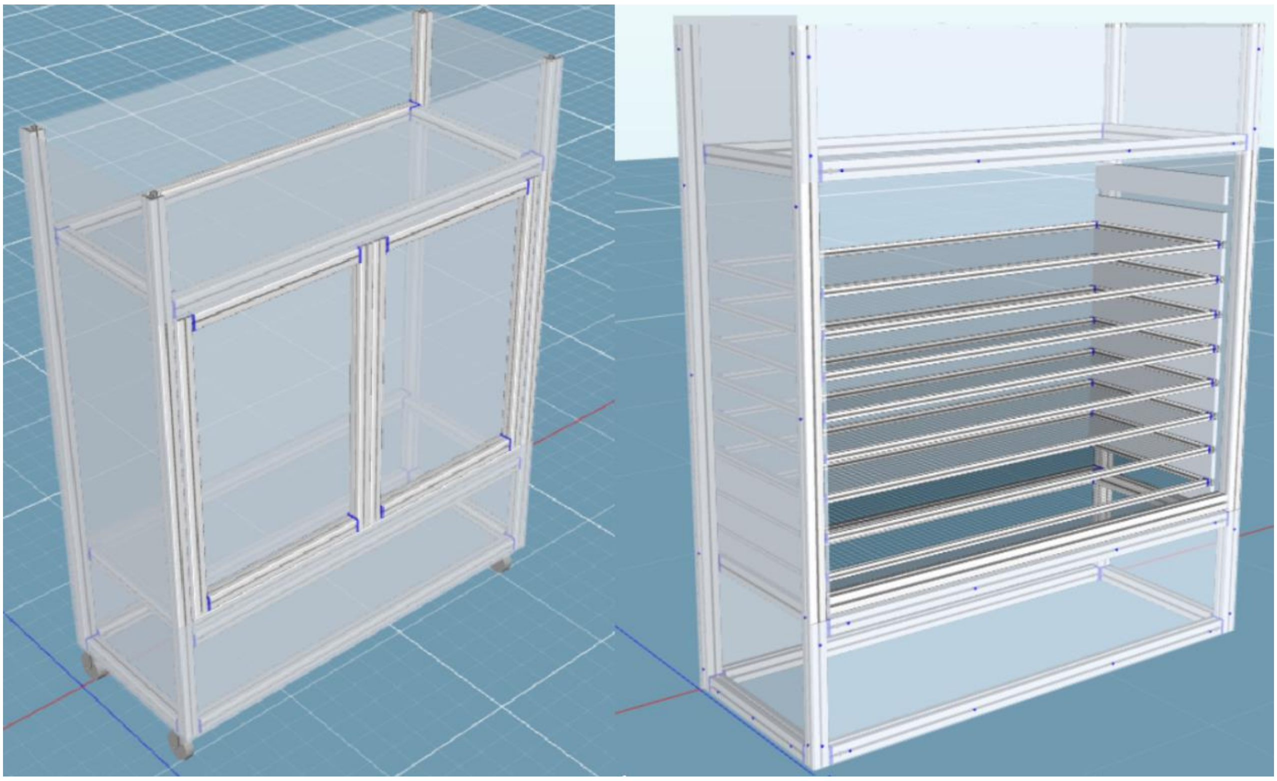


Fig. 29. View of rain test bench frame (1500x600x1950mm) with shelves

In conclusion, this newly developed rain test bench could cover all manufactured meters. The new testing chamber would be able to fit all water meters manufactured per day. Compared to the temperature and humidity chamber which is used now, this new one would not leave any watermarks on meters, and it would dry meters up, making them ready for packing. In the time frame perspective, new test bench would be able to do the same ten temperature change cycles adding the additional meter drying procedure. All root causes of humidity inside meter housing was not found, but with using this new rain test bench, the elimination of faulty meters is done, making sure they will not reach the client. By assuring only highest quality meters leaving the factory, a team is buying time to complete testing and inspection in other fields of production to find other root causes of the discussed problem in the future.

8. Cost of solution implementation

There are a few aspects that need to be calculated to understand if the development of a new rain test bench would be financially worth it. The humidity inside the meters problem is very harmful not only economically but also for the company X reputation. When the client finds already installed faulty meters, it is terrible for the company image. This problem can only be fixed by solving it the right way, making the client sure that everything is done to eliminate faulty meters in the factory of the company X. Since contracts with clients based in countries with extreme environmental conditions extend for years, it is essential to maintain a good and trusting business relationships. From this perspective developing the new test bench is worth it because it guarantees that the company is reducing faulty meters percentage from 2% to zero in a perfect scenario.

Besides the reputation and business relationships side, there is the financial side where the cost of the new rain test bench must be calculated to make sure that it will pay off. The main goal of the company X is to make money and gain profit, so the cost of the new system development and implementation must be low enough to make a profit.

To calculate the cost of the problem solution implementation, all variables that affect the price must be gathered. First, the most expensive part of this calculation is the rain test bench itself. Secondly, a person is needed who will have additional duty to maintain this testing operation, inspect all meters to find faulty ones, change meters between testing, repeatedly check if the process goes smoothly. The factory works in three shifts per day, so since test bench works for 24 hours uninterrupted, either three more people need to be hired, or these tasks can be assigned to already working employees. This operation does not take that much time, so new employees are not necessary. There is a need for someone capable of doing such work. After implementing the new rain test bench and get it working, a research and development quality assurance team will move on to finding other root causes of the humidity inside the meters problem.

By eliminating the cost of hiring new employees, the cost of water, electricity and the factory space will also be eliminated from the calculation. This cost of problem solution implementation calculation is based on the cost of developing a new rain test bench, the cost of replacing all faulty meters if a new test bench would not be developed. The cost of replacing meters includes the cost of clients work to replace installed meters in the field, the cost of transportation of faulty meters back to Lithuania and the cost of producing new meters which would be added to the next shipment. It is important to note that the plan was to send an additional quantity of meters with the main batch for the client to have spare ones in case of such a situation.

There was an agreement during the 8D problem-solving team meeting to not apply any containment of meters until the solution to eliminate faulty meters was found. By now, much more units have reached the client, and these meters are being installed in the field. This means that the company X is taking the responsibility of replacing 2% or even more faulty meters if they turn out to have the humidity inside after some time of the exploitation. Combining contracts with all clients based in countries with extreme environmental conditions, the quantity of water meters needed to produce by the end of this year is reaching 100 000. By implementing the new rain test bench, the company is making sure that the meters leaving the factory from now on will not have this problem. One water meter costs 63 Eur (depending on the specific contract), so replacing 2% of already installed meters would be the number of units installed times 0,02 times 63 Eur. Since the quantity of installed meters is much higher than the amount of the meters tested, the percentage of installed faulty meters could be higher than 2%.

The company X will need to replace some quantity of installed water meters in the future because some of them will have the humidity inside the housing. This number should be around 2 per cent but could be higher. The number of already installed meters is 20 000 through all clients based in countries with extreme environmental conditions. In table 11, the quantity of meters which will need to be replaced is shown with and without the new testing solution implementation.

Table 11. Quantity of faulty meters

Quantity of meters	Quantity of faulty meters (2%)	Cost of replacing faulty meters
20 000 (installed)	400 (replacement is unavoidable)	400*63 Eur + transportation and replacement costs
80 000 (to be installed)	1 600 (replacement is avoidable if new test bench is implemented)	1 600*63 Eur + transportation and replacement costs

By implementing the new testing solution, the number of faulty meters that would reach our clients could be reduced by 1 600 units. Since meter price is 63 Eur, the total cost of replacing faulty meters would be 100 800 Eur. If transportation and replacement costs are added, this number can be doubled. In total, the cost is 201 600 Eur. The good news is that it is avoidable. The bad news is that there are already 20 000 units installed and the cost of replacing 2% of the quantity will be 25 200 Eur plus transportation and replacement costs. By implementing a newly developed testing solution, the company X could save 200 000 Eur.

To calculate the cost of problem solution implementation, which is a new rain test bench, the cost of meters the company will need to replace unavoidably and the cost of the solution implementation are added. Price of all test bench components is provided in table 12. Prices are taken from private company X agreements with different companies providing these products.

Table 12. Price of rain test bench components

Nr.	Component	Price, Eur
1	Aluminium 45x45mm profile	1 000
2	Frame connections	1 200
3	Pipe Heizko, Ø26mm	85
2	PVC-U plastic for frame	600
2	Salenoid valve SCG238 046 - 21HT4K0Y160 [22]	170
4	Water pump Speroni RSM 5, 1,4kW [23]	135
5	W–W heat exchanger ZC250HP-10P [24]	165
6	Instantaneous water heater Kospel PPH2-9 12kW [25]	145
7	Water cooler RS20 20kW Neoair [26]	250
9	Water collector [28]	30
10	Suction fan Haushalt 150X1 [29]	20
12	Electric 2kW PTC heater B2 [30]	200
13	Cost of employee (with taxes)	1 500
	Total price:	5 500

Adding the cost of a new rain test bench and meters that the company will need to replace the cost is 5 500 Eur plus the cost of replacing 400 meters. The payback of the rain test bench is calculated, dividing the cost of the rain test bench from the cost of the meter. The new solution of the problem will payback after keeping 88 water meters from reaching clients. The cost of rain test bench includes the cost of designing and testing, also manual labour of an employee to assemble all parts into one working system. This work should take about 15 working days, so the cost of an employee is 1 500 Eur with taxes. If this rain test bench would not be implemented, the cost of replacement of all faulty meters would be significantly higher than implementing test bench and eliminating all faulty meters. So, to conclude the cost calculation, the company X must think about reputation benefits which will be gained by implementing the new test bench. Also, the financial cost of the problem solution implementation is significantly lower than potentially replacing two or more per cent of all water meters X. Instead of doing nothing and potentially losing clients or covering replacement costs which are very high, the company will implement the new testing solution and assure only high-quality meters leaving the factory.

9. Further recommendations

Based on the performed experiment and its results, it is clear that further work regarding this problem in the water meter X must be done. A team managed to find the problem solution which works perfectly fine for now, but it is crucial to find other root causes of this problem to eliminate it from the production entirely. The aim of this project was to develop the quality problem solution for the plastic injection moulded housing, and it is reached successfully.

As the company is growing and the number of clients is expanding, naturally at some point the suggested solution will be not enough. In the future, newly proposed rain test bench could be improved by increasing the number of meters tested at once. This improvement could create better production flow by making the testing process more efficient. Since the quality problem solution can extract faulty meters from the production in the future, the number of cycles could be increased. There is a chance that after testing meters for a much more extended period, more of them would show defects. The another possible improvement that could be made would be creating even more extreme environmental conditions by increasing the range of temperature changes and the speed of temperature going up and down. These improvements will require more powerful equipment, possibly even some safety features. It would also require much more resources and floor space. Now future improvements are not needed because the proposed quality problem solution is fully capable of dealing with testing quantity coverage and required speed.

Conclusions

1. Based on literature analysis experiment was performed in the plastic injection moulding process. It helped to identify parameters and conditions influencing water meter X plastic housing quality problems. The most influential parameters are holding time and holding pressure.
2. Initial analysis of received faulty meters showed many meters geometry of housing top bell part out of tolerance range. The experiment is performed by producing samples when applying changes in the plastic injection moulding process parameters. From 25 different parameter setups, the combination resulting in the smallest deviation from desired geometry is selected and applied to the future production. It reduces the number of faulty meters down to 2%.
3. Water meter X quality problem solution is proposed by implementing rain testing method. It replicates extreme environmental conditions with temperature changes between 20°C and 70°C, which causes the quality problem to appear. It reduces faulty meters, which are leaving factory, quantity from 2% to 0,02%, which is the desired limit. The development of a new test bench is proposed with the ability to test 1 000 meters per day. It would be capable of recreating extreme environmental conditions with the same temperature changes and eliminating the bottleneck effect in production.
4. The financial losses caused by the quality problem are calculated, and reputational damage is discussed, proving the necessity of a problem solution implementation. Financial losses caused by quality problem could reach 200 000 Eur. The new test bench implementation cost is 5 500 Eur, and this investment would payback after finding 88 faulty meters. It is cheaper than the potential cost of replacing already installed faulty meters.

List of references

1. Most Common Thermoplastics Used in Injection Molding. [online]. [Accessed 01 April 2020]. Available from: https://www.midstatemold.com/common-thermoplastics-injection-molding/
2. Plastic Molding: Understanding The Types | The Rodon Group®. [online]. [Accessed 02 April 2020]. Available from: https://www.rodongroup.com/blog/plastic-injection-molding-101-the-types
3. Plastic Injection Molding Machines: Types and Benefits. [online]. [Accessed 02 April 2020]. Available from: https://www.midstatemold.com/injection-molding-machines/
4. Major Advantages of Plastic Injection Molding | The Rodon Group®. [online]. [Accessed 02 April 2020]. Available from: https://www.rodongroup.com/blog/6-major-advantages-of-plastic-injection-molding
5. Plastic injection moulding machine example. [online]. [Accessed 02 April 2020]. Available from: https://www.engelglobal.com/en/uk/products/injection-molding-machines/victory.html
6. ZHOU, Xundao, ZHANG, Yun, MAO, Ting and ZHOU, Huamin. Monitoring and dynamic control of quality stability for injection molding process. Journal of Materials Processing Technology. 1 November 2017. Vol. 249, p. 358–366. DOI 10.1016/j.jmatprotec.2017.05.038.
7. VOJNOVÁ, Eva. The benefits of a conforming cooling systems the molds in injection moulding process. In : Procedia Engineering. Elsevier Ltd, 1 January 2016. p. 535–543.
8. KOVÁCS, J. G. and SIKLÓ, B. Test method development for deformation analysis of injection moulded plastic parts. Polymer Testing. 1 August 2011. Vol. 30, no. 5, p. 543–547. DOI 10.1016/j.polymertesting.2011.04.011.
9. MARTÍNEZ-MATEO, I., CARRIÓN-VILCHES, F. J., SANES, J. and BERMÚDEZ, M. D. Surface damage of mold steel and its influence on surface roughness of injection molded plastic parts. Wear. 29 July 2011. Vol. 271, no. 9–10, p. 2512–2516. DOI 10.1016/j.wear.2010.11.054.
10. KURT, Mustafa, SABAN KAMBER, O., KAYNAK, Yusuf, ATAKOK, Gurcan and GIRIT, Oguz. Experimental investigation of plastic injection molding: Assessment of the effects of cavity pressure and mold temperature on the quality of the final products. Materials and Design. 1 September 2009. Vol. 30, no. 8, p. 3217–3224. DOI 10.1016/j.matdes.2009.01.004.
11. MERCADO-COLMENERO, Jorge Manuel, RUBIO-PARAMIO, Miguel Angel, MARQUEZ-SEVILLANO, Juan de Juanes and MARTIN-DOÑATE, Cristina. A new method for the automated design of cooling systems in injection molds. CAD Computer Aided Design. 1 November 2018. Vol. 104, p. 60–86. DOI 10.1016/j.cad.2018.06.001.
12. PARK, Hong Seok, PHUONG, Dang Xuan and KUMAR, Saurabh. AI based injection molding process for consistent product quality. In : Procedia Manufacturing. Elsevier B.V., 1 January 2019. p. 102–106.
13. Smart Switchgear for Extreme Installation Environments. [online]. [Accessed 16 May 2020]. Available from: https://www.cired-repository.org/handle/20.500.12455/294
14. FU, Junyu and MA, Yongsheng. A method to predict early-ejected plastic part air-cooling behavior towards quality mold design and less molding cycle time. Robotics and Computer-Integrated Manufacturing. 1 April 2019. Vol. 56, p. 66–74. DOI 10.1016/j.rcim.2018.08.004.
15. CRISAN, N., DESCARTES, S., BERTHIER, Y., CAVORET, J., BAUD, D. and MONTALBANO, F. Tribological assessment of the interface injection mold/plastic part. Tribology International. 1 August 2016. Vol. 100, p. 388–399.

DOI 10.1016/j.triboint.2016.04.015.
16. BLEY, Grosse, GROSSE BLEY, Werner, KISTER, Gerhard, BERGMANN, Joachim and WOLDT, Erik. (12) United States Patent45) Date of Patent: (54) Method for testing the tightness of water conducting components in a housing (75) Inventors: S371 (c)(1), (2), (4) (30) Foreign Application Priority Data. 2015.
17. BEECH, Dennis W. Plastic tube sealing and test system. 2010.
18. KASHYAP, Satadru and DATTA, Dilip. Process parameter optimization of plastic injection molding: a review. International Journal of Plastics Technology. 1 June 2015. Vol. 19, no. 1, p. 1–18. DOI 10.1007/s12588-015-9115-2.
19. SOUSA, Sergio Dinis. The 8D Methodology: An Effective Way to Reduce Recurrence of Customer Complaints? Quality control in industry 4.0 context View project [online]. 2010. [Accessed 16 May 2020]. ISBN 9789881821089. Available from: https://www.researchgate.net/publication/45534757
20. FISCHER, Jerry M. Handbook of Molded Part Shrinkage and Warpage. Handbook of Molded Part Shrinkage and Warpage [online]. 2003. [Accessed 16 May 2020]. Available from: https://books.google.lt/books?hl=lt&lr=&id=IMF-oSmA1BcC&oi=fnd&pg=PP1&dq=Handbook+of+Molded+Part+Shrinkage+and+Warpage&ots=pVyAru66gC&sig=EcphwOHKwO6Fv87cOf6Onyj50ec&redir_esc=y#v=onepage&q=Handbook of Molded Part Shrinkage and Warpage&f=false
21. IP68 and IP65 water jets requirement comparison. [online]. [Accessed 01 May 2020]. Available from: https://en.wikipedia.org/wiki/IP_Code
22. Salenoid valve SCG238 046 - 21HT4K0Y160. [online]. [Accessed 05 May 2020]. Available from: https://auregis.lt/solenoidinis-voztuvas-scg238?search=vožtuvas
23. Water pump Speroni RSM 5, 1400 W. [online]. [Accessed 05 May 2020]. Available from: https://www.senukai.lt/p/elektrinis-vandens-siurblys-speroni-rsm-5-1400-w/2eo2?mtd=search&pos=regular&src=searchnode
24. W–W heat exchanger ZC250HP-10P. [online]. [Accessed 05 May 2020]. Available from: https://www.brgroup.eu/lt/produktai/silumokaiciai.htm
25. Instantaneous water heater Kospel PPH2-9. [online]. [Accessed 05 May 2020]. Available from: https://www.senukai.lt/p/momentinis-vandens-sildytuvas-kospel-pph2-9-9kw/bsyr?cat=b86&index=1
26. Water cooler RS20 20KW Neoair. [online]. [Accessed 06 May 2020]. Available from: https://www.senukai.lt/p/kaloriferis-vandeninis-rs20-20kw-neoair/5x3b?mtd=search&pos=regular&src=searchnode
27. Water pipe Heizko, Ø26mm. [online]. [Accessed 06 May 2020]. Available from: https://www.senukai.lt/p/daugiasluoksnis-vamzdis-heizko-o-26-mm/323g
28. Water collector. [online]. [Accessed 06 May 2020]. Available from: https://www.senukai.lt/p/kolektorius-carlo-poletti-c323n10qr-1-x-1-2-in-3-ziedu-karstam-vandeniui/50b0?cat=b8o&index=16
29. Suction fan Haushalt 150X1. [online]. [Accessed 06 May 2020]. Available from: https://www.senukai.lt/p/istraukiamasis-ventiliatorius-haushalt-150x1/5we1
30. Electric 2 kw PTC heater B2. [online]. [Accessed 06 May 2020]. Available from: http://www.masterheaters.lt/elektriniai-sildytuvai-b-2-ptc,325.html