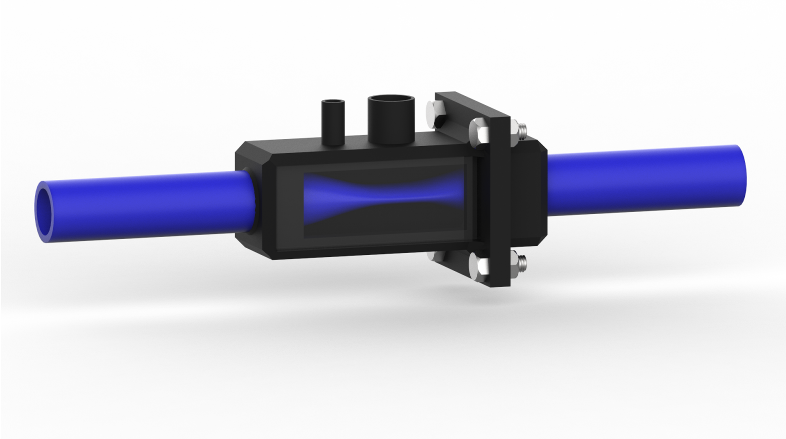
Kungliga Tekniska Högskolan

Mechatronics Advanced Course 2022

Final Report



Electronically Vacuum Regulated Shut-off Valve for Milking System

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Abstract

This report was part of a capstone project course for the Mechatronics track at KTH Royal Institute of Technology. This project was conducted in collaboration with DeLaval International AB. DeLaval is a producer of dairy farm machinery and equipment. This project aimed to solve a problem that occurs during a typical milking process of a cow. The problem in question is a decrease of suction at the teats of the cow as the milk flow increases. The main stakeholder requirement was to develop a new electronically vacuum-regulated valve that eliminates this decrease of suction as the milk flow varies. A test rig was built to imitate a real milking system and to test possible design solutions. The final valve design implemented was an inverted pinch valve which is pneumatically actuated by a vacuum signal. Testing showed that a convincing majority of DeLaval's requirements could be satisfied.

Acknowledgements

We would like to thank Daniel Brun and Andreas Edmark from DeLaval for providing us with such a fascinating project and offering their continuous feedback and support. We would also like to thank our project coach, Nils Jörgensen, for his clear guidance and insightful advice regarding the project's approach. Finally, we would like to thank the Mechatronics department at KTH for supporting our work.

DeLaval HK Team,
Stockholm, December 2022

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Chapter 1

Introduction

This project was part of the higher courses, MF2058 and MF2059, given by KTH. Students are divided into groups of 8 people, tasked to conduct a mechatronics project given by a stakeholder. In this chapter, the background and purpose of the project are presented as well as the established requirements given by the stakeholder.

1.1 Background

Cow's milk has been utilized by humans for many thousands of years, going back as early as 7000 BC[1]. Ever since then, new milking methods have been developed and today, most milking processes involve some sort of milking machine. The main motivation for the development of machine milking processes was to increase the efficiency of milk production and to reduce labor requirements on dairy farms[2]. The development of milking machines started in the late 19th century[3]. After many years of research, the two-chambered teat cup with cyclic opening and closure of a rubber liner was examined to be the best solution for machine milking[4]. This design allows the pressure to be changed periodically in the teat cup chamber. Around the liner in the chamber, a pulsator is connected that generates a pulsating effect which opens the teat cup liner to allow the milk to flow and then closes the liner around the teat again to massage the tissue and reduce congestion[5]. The teat cups are located in a milking cluster, which collects the milk and transports it down the milk tube[6]. A vacuum pump is extracting air continuously from the system which enables the milk to flow from the cluster all the way down to the milk container[7].

The word vacuum refers to below atmospheric pressure, and sometimes the term negative pressure is used[7]. In the context of milking machine measurement, vacuum refers to any pressure below atmospheric pressure, specified as the reduction below ambient atmospheric pressure[8]. Therefore, the vacuum drop mentioned in this project represents a pressure increase in the milking system with a resulting pressure that is still lower than atmospheric pressure. There are devices in vacuum systems that regulates and controls the vacuum to enhance the milking performance. Typical vacuum regulators allow excess air to enter the system or vary the volume capacity of the pump[9]. Even though the vacuum produced is steady and regulated to the expected level, there is still a vacuum drop at the milking cluster[10]. In absence of milk flow, the vacuum at the cluster is close to full system vacuum level, but the pressure at the cluster drops significantly as soon as milk is present and transported in the milk tubes[11]. An accumulation of milk in the cluster and the milk tubes affects the free airflow and leads to a decrease in vacuum at the teat cups. This behavior has been defined as a vacuum drop[12]. Fluctuations and drops in the teat-end vacuum occur regularly during machine milking as a result of various interactions between vacuum supply, teat cup liner movement, and milk flow[13]. Milk flow-dependent vacuum drops can not be completely avoided with current milking systems[14], as the milk tube is responsible for both providing vacuum to the cluster and transporting the extracted milk to the milk container.

While there is no scientific evidence available that vacuum drops should be completely avoided as long as the remaining vacuum is high enough to close the liner adequately, research has demonstrated that the minimum cluster vacuum is the main influence on milking performance, independent of the level of the system vacuum and related vacuum drops[2, 15]. There is an inverse relationship between milk flow rate and cluster vacuum with the highest cluster vacuum occurring at the lowest milk flow rate. Teat tissue stress is most severe during low flow periods of milking, when the teat-end vacuum level is the highest[16]. This may not only reduce milking performance through reduced efficiency of milk removal[17], but it can also compromise the condition of the teats and reduce the massage effect of the closed liner on the teat[14]. To address these issues, it has been suggested to use a control strategy to regulate the vacuum in the milk line. One of the research groups has shown a significant improvement with this approach[18], although the design is relatively simple and mechanically controlled. To achieve this function in a vacuum system, sensing techniques are essential.

Therefore, it is favorable to apply a dynamic control strategy to adjust machine settings during milking of an individual animal. This project intended to construct a new type of electrically controlled valve, placed in the milk tube to regulate the vacuum at the cluster with the help of pressure sensors.

1.2 Scope

As this was a Mechatronics master's project at KTH with a time limit of approximately six months, the team was limited to focus on these points:

- Construction of a rig to test possible solutions.
- Development of a new electronically vacuum-regulated valve for milking systems.
- Design of a feedback controller to eliminate the decrease of vacuum as the milk flow increases.

The solution is supposed to be applicable to the existing milking systems that DeLaval offer to their customers, and therefore needs to be modular and cheap to achieve the requirements.

1.3 Requirements

In this section, detailed lists of Stakeholder Requirements (**SR**) and Technical Requirements (**TR**) are provided. The stakeholder of this project is DeLaval.

1. **SR 1** A new shut-off valve shall be designed while considering food contact regulations and the vacuum drop over the shut-off valve shall be less than 1 kPa at 10 L/min with fully open valve.
2. **SR 2** The requirements regarding vacuum regulation concern the Low line configuration
3. **SR 3** Impose an upper limit on system vacuum
    - **TR 1** Max 55 kPa
4. **SR 4** The unwanted vacuum drop caused by milk flow shall be reduced/eliminated using sensor feedback to the new shut-off valve
    - **TR 2** At flow 0 L/min–10 L/min and a reference value between 30 kPa–50 kPa at the cluster, the vacuum variation must be less than ±1 kPa
    - **TR 3** At flow 10 L/min–14 L/min and a reference value between 30 kPa–50 kPa at the cluster, the vacuum variation must be less than ±2 kPa
5. **SR 5** The positioning of sensors and other electronics shall not limit/affect the serviceability of equipment
    - **TR 4** The design should be modular (interchangeable parts)
    - **TR 5** The design should be robust enough to withstand water, dirt, etc.
6. **SR 6** All newly designed equipment that shall be used in the system must fulfill food contact regulations (**ISO-standard 5707:2007**[19]).
    - All components that are subjected to a vacuum shall be designed and constructed to withstand a minimum vacuum of 90 kPa without permanent distortion.
    - Materials in contact with milk shall meet requirements for food contact surfaces. All materials in contact with milk or cleaning solutions, whether used for rigid components or flexible components shall be constructed to withstand the maximum temperature used in the plant as specified in the user's manual. In addition, such materials, when used in accordance with the recommendations in the user's manual, shall not impart taint to the milk.
    - All milk contact surfaces shall be free from engraving or embossing. All metal milk contact surfaces, except for welded seams, shall have a surface roughness, Ra, less than or equal to 2.5 µm when tested in accordance with ISO 4288. Surface roughness, Ra, on welded seams shall not exceed 16 µm.

- Copper or copper alloys shall not be used in any part of the installation that may come into contact with milk or cleaning and disinfecting fluids other than water. Materials that come into contact with cleaning and disinfecting fluids at concentrations of normal use shall be suitable for such contact.
- Materials that also come into contact with milk shall be resistant to both milk fat and cleaning and disinfecting solutions.

7. **SR 7** The vacuum regulation must be tested and pass at least one edge case.
   - **TR 6** Fall off/kick-off - the whole cluster falls of the teats. Stop vacuum.
   - **TR 7** Slip - the teat cups have some miss alignment with the teats which causes some air leakage. Control the vacuum so the teat cups get aligned correctly again.
   - **TR 8** Start of milking - during the start of milking a temporary air inlet is created. The amount and duration are dependent on the skills of the milker, the vacuum control must handle this case.
8. **SR 8** A test rig must be built so the students can perform tests at KTH and not be dependent on being at DeLaval during the test process.

1.4 Delimitations

Due to limitations in time and cost, this project was adapted to utilize as many parts supplied by DeLaval as possible. This helped to reduce delivery times and costs. In order to meet the deadline, the team decided on a project design in the concept evaluation section and then implemented it, rather than implementing and comparing the performance of all designs. Usually there are multiple milk clusters connected to the same system vacuum but this project was limited to only one. For practical reasons, the test rig used water instead of milk as the characteristics of the liquids are similar enough for the scope of the project.

1.5 Readers guide

This report is divided into eight chapters and an appendix, which contents are described below.

Introduction

The introduction gives the reader a brief overview of the project, some background information, stakeholder requirements, and limitations.

State of the Art

The state-of-the-art chapter includes background theory to relevant areas of the project. It includes the current solution used in milking systems, the reason for the drop in vacuum, valve alternatives, controllers, sensors, and the test rig design DeLaval is currently using.

Concept Evaluation

In the concept evaluation chapter, the potential project designs are discussed and evaluated with a design evaluation matrix. From the evaluation, the most promising design is selected to be implemented in the test rig.

Method

The methodology chapter discusses the project structure including the timeline, work arrangement, and risk analysis.

Implementation

In the implementation chapter, the test rig and its components are described in detail. This includes the concluded valve solution and the process of verifying the test rig.

Results

The results chapter presents all results of the project including the verification of the test rig, the performance of the current solution, and the new valve solution. Results from tests performed on individual components and tests with various configurations are also included.

Discussion and Conclusion

In the discussion and conclusion chapter, the results from the previous chapter are discussed and related to the stakeholder and technical requirements. Potential improvements and alternate designs are also discussed.

Future work

The future work chapter gives recommendations on the direction of future work and possible areas of improvement.

Appendix

In the Appendix, chapter figures of the components, CAD files, data sheets, code used in the microcontroller and other project relevant documents can be found.

Chapter 2

State of The Art

In this chapter all the relevant background and information needed to understand the project are presented. The state of the art is then acting as the foundation for the choice of Design Concept in the next chapter.

2.1 Current Milking System

The current design of the milking system from DeLaval consists of a milk cluster, a milk meter (flow meter), a pulsator and a pneumatic diaphragm valve. It can be seen in Figure 2.1. The milking cluster is attached to the teats of the cow and it is connected via a milk tube to a milk meter followed by a mechanical shut-off valve and then the main milk line. To perform an effective milking, the vacuum under the teat should be stable during the whole session. The current design of the shut-off valve mechanically regulates the milk tube vacuum using a membrane that will open or close depending on the difference between the control vacuum and the milk tube vacuum. A pulsator is used to imitate the calf nursing. The purpose is to provide a pulsating vacuum to the inner liner of the teat cup. In combination with this, a small air inlet on the cluster allows milk to flow. The method of driving the pulsator can vary. Pneumatic and electronics are some examples, but the functionality is the same. With this mechanically regulated vacuum system there are some potential problems that are unfavorable for a stable vacuum level throughout the system. Some of the problems are that the shut-off valve shows regulation problems, self-oscillation, and a built-in vacuum drop (by design). The geometrical design and material selection in the shut-off valve is limited by food contact regulations.

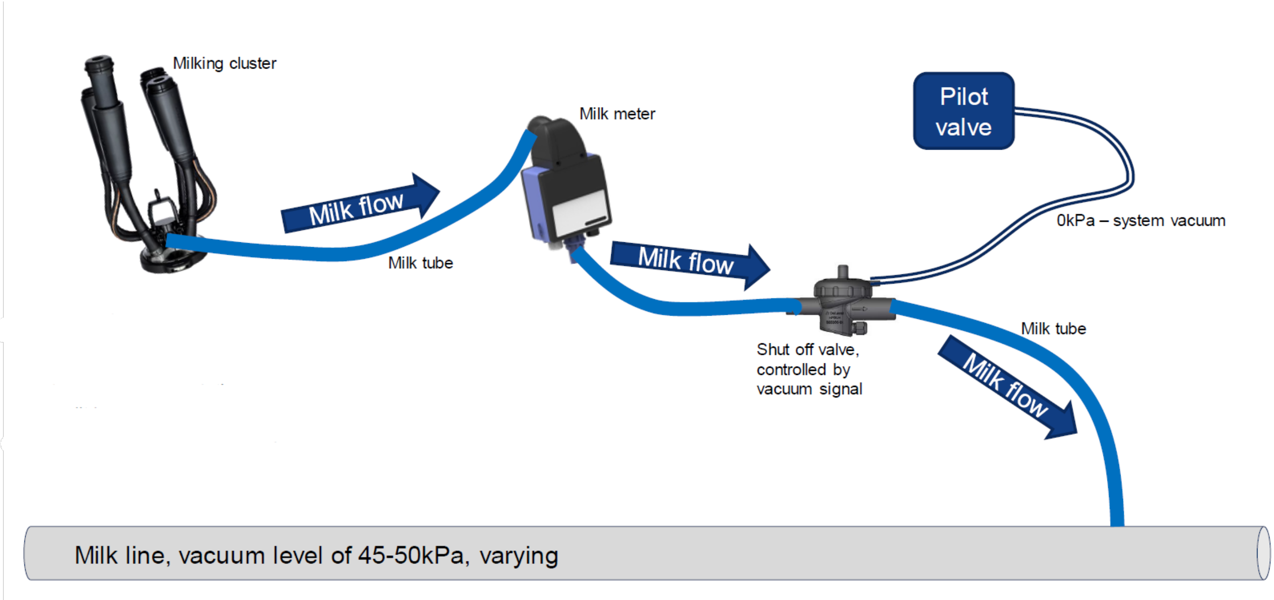


Figure 2.1: The current solution used by DeLaval.

Vacuum Drop Analysis

Based on Bernoulli's equation, the vacuum drops in a milking machine tube can be simply expressed as

$$\Delta P = (1-\alpha)\rho_m g H + (1-\alpha)\lambda\rho_m \frac{L_t}{D}\frac{u_M^2}{2} + (1-\alpha)\xi\rho_m \frac{L_t}{D}\frac{u_M^2}{2}, \tag{2.1}$$

where ΔP is the vacuum drop, α is the volumetric air coefficient in the long milk tube, ρ_m is the density of milk, H is the height the milk flow dropped, L_t is the tube length, D is the diameter of the tube. u_M is the sum of the reduced velocities of milk and air mixture, λ is linear loss coefficient and is dependent on the relative roughness of the tube and the Re number and finally, ξ is the local loss coefficient. So, its assumed that the pressure P_c in the cluster is operating pressure P_o plus vacuum drop ΔP, $P_c = P_o + \Delta P$. Furthermore, Golisz etc.[20] determined the volumetric air coefficient α and simplified Bernoulli's equation.

Furthermore, these polynomials can be simplified in a symbolic form as

$$\varepsilon_4 x^4 + \varepsilon_3 x^3 + \varepsilon_2 x^2 + \varepsilon_1 x + \varepsilon_0 = 0, \tag{2.2}$$

and there will be no zero roots for these polynomials since ε_0 is always a positive constant value, which means the vacuum drop will never equal zero regardless of the milking system constructions and milk flow. The vacuum drop will also increase as the flow rate increases, as equation 2.1 implies. To control the valve, the flow rate is also required to sense the pressure behavior somewhere in the tube instead of directly at the cluster. The detailed equation can be found in Appendix A.1.

2.2 Competitive Technologies

In the food-, pharmaceutical- and chemical industry it is desirable to separate the flowing medium from the internal mechanisms of the valve, as it could potentially trap contaminants. To avoid dead volume and small chambers in the internal mechanics of valves, one solution is to use a pinch valve. A pinch valve features an internal sleeve that keeps the flow medium completely isolated and protected from contaminants.

For similar applications, a diaphragm valve is often used. A diaphragm valve has a membrane pressed or sucked down upon a surface to stop the flow. It features geometrical disturbances but is less flow disruptive than solenoid valves. The wide selection of materials of the internal tube and membrane makes the valve customizable, which makes it adaptable to a variety of industries depending on specific requirements. When selecting sleeve and membrane materials, durability needs to be considered as well as food contact regulations. Each closing and opening cycle puts strain on the material and in abrasive and corrosive applications they often outlast alloy metal valves[21].

A pinch valve with a larger clamping area would reduce the plastic deformation and increase the durability of the valve[22]. In water and waste treatment industries, the pinch valve handles several different media containing sludge, grit, and garbage. This suggests that with proper dimensions and sleeve material the valve will be able to handle the lumps in the milk. This is mainly due to the smooth surface without obstructing pockets. Both valves can be designed proportionally, meaning that the valves can be partially open to have further control of the flow through the valves. The valves can be actuated both pneumatically and mechanically.

In the automotive industry, proportional valves are used for controlling the air intake to cars. The conventional way of controlling the valves is using pulse width modulation (PWM)[23]. In a similar application, a pinch valve was used to regulate the air pressure in a sprayer valve. The sprayer valve was used in an agricultural watering system. The system was modeled as a linear system and initially controlled with a reduced-order observer model. However, the controller achieved a better control performance with a proportional-integral controller[24]. The research shows that a pinch valve could be a feasible alternative to use in the milking system.

2.3 Valve

The currently used shut-off valve used by DeLaval is a membrane valve, which is a mechanically self-regulating valve that opens and closes depending on the difference between the control vacuum and the milk tube vacuum. Some valve alternatives are presented below.

Globe Valve

Globe valves work by lifting a plug out of the flow path. As the globe valve is opened, it allows the fluid to flow. While being superior in terms of control and precision, there are some problems with this solution. Dead volumes are located both at the bottom of the duct and the gap between the control rod and the wall. These make it hard to clean after use and do not comply with food safe contact regulations, see Figure 2.2[19].

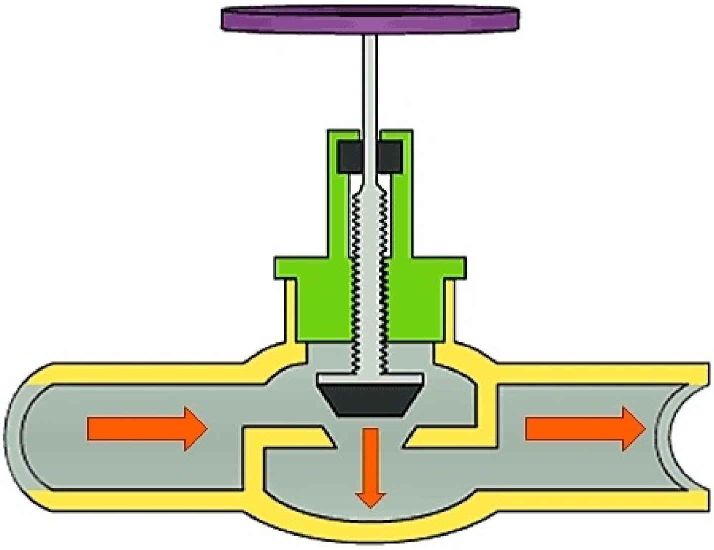


Figure 2.2: Globe valve[25].

Solenoid Actuator

A solenoid actuator is an electrically controlled actuator. The actuator features a solenoid, which is an electric coil with a movable ferromagnetic piston in its center. While powered off, the piston closes off a small orifice. An electric current through the coil creates a magnetic field. This magnetic field exerts an upwards force on the plunger opening the orifice proportionally to the input. Similarly to the globe valve it features small internal parts where contaminants could be trapped which do not comply with food contact regulations[19].

Pinch Valve

Pinch valves are usually mechanically actuated but there are variations where the valve is pneumatically actuated. It utilizes pressurized air to open and close the valve, which can be seen in Figure 2.3. In the open position, the valve has no geometric restrictions and allows a wide range of media to pass through the valve. The flexible internal food-safe rubber sleeve in the valve keeps the media isolated preventing any risk of contamination and making it easy to clean[26].

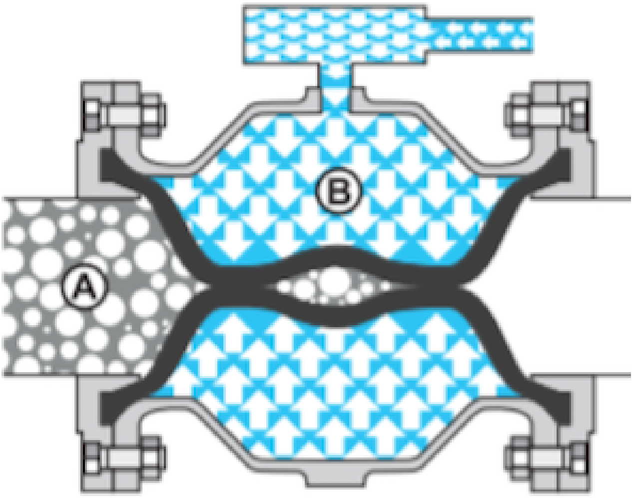


Figure 2.3: Pneumatic pinch valve[27].

Diaphragm Valve

As mentioned in 2.2, the diaphragm of the valve is a flexible pressure-responsive part. This part delivers force to regulate, shut, or open the valve. This type of valve is very similar to a pinch valve, but it uses an elastic membrane instead of a flexible liner to isolate the fluid from the closure part. The valve can be actuated both pneumatically and mechanically.

2.4 Sensors

There are two different types of sensors to be used in this project. Ceramic pressure sensors to read the vacuum level in the system and a flow meter to read the flow of water through the milk tube. The ceramic pressure sensor that will be used is from Metallux, see Appendix A.3. It collects readings from the reactive movement of a membrane inside of the housing and converts it to an electric signal following the piezo-resistive principle. In this case, it will react to the vacuum in the milk tube. This specific sensor is applicable to the food industry because the flush-front diaphragms make for easy cleaning, which is an important requirement for sensors used in the food industry.

A different sensor used in the milk industry is a milk meter. It is used in DeLaval's current system to measure the flow and condition of the milk using infrared technology, see Appendix A.4. This helps the farmer to monitor the livestock's health and milk production. This type of sensor will not be utilized in the scope of this project for two reasons: The infrared technology in the sensor only works with milk and not water, which will be used in the test rig. The milk condition data it collects is also of no use when it comes to regulating the vacuum level in the system. It will however be a part of the test rig, in order to include the vacuum drop it generates.

2.5 Controller

The successful implementation of control valves within hydraulic systems in the chemical industry[28] gives an indication of the applicability of control in the context of automated milking systems. In the chemical process industry, extreme precision is required compared to the type of control needed for automated milking due to the impact it has on the final product. Hence, it becomes trivial that implementing a controller in automated milking machine systems is of great interest since it has not been done in state-of-the-art systems as of 2021[18].

Kalman Filter

The Kalman filter is a powerful tool for analyzing and predicting the behavior of dynamic systems. It is based on the idea of using a series of measurements observed over time, in conjunction with a model that describes the system being studied, to produce estimates of the underlying state of the system[29]. The filter uses a two-step process to produce these estimates. First, it makes an initial estimate of the state of the system based on the current measurement and any previous estimates. Then, it refines this estimate using additional information from the system model and the current measurement. This process is repeated over time, with the filter constantly updating its estimates of the system state. The Kalman filter has several advantages over other methods for estimating the state of a dynamic system. One key advantage is that it is able to take into account both the current measurement and any previous estimates of the system state, which can provide a more accurate estimate than using only the current measurement. Additionally, the Kalman filter is able to handle situations where the system being studied is subject to noise or other types of uncertainty, which can make it difficult to get accurate estimates using other methods. Finally, the Kalman filter is relatively simple to implement and can be applied to a wide range of systems, making it a useful tool in many different fields. In this project, the object to be controlled is the vacuum level at the cluster. Since there will not be any direct detection at that spot, a Kalman filter will estimate the state at the cluster using the sensor placed far from the cluster and using the readings of the flow rate of milk.

2.6 Test Rig

DeLaval currently uses a test rig in their laboratory for testing their milking system. It is usually favourable to test milking equipment on a test rig before testing in real milking environments to reduce risks and increase efficiency. Since building a test rig was a requirement from the stakeholders, **SR 8**, a test rig was built to replicate what DeLaval currently uses.

Chapter 3

Concept Evaluation

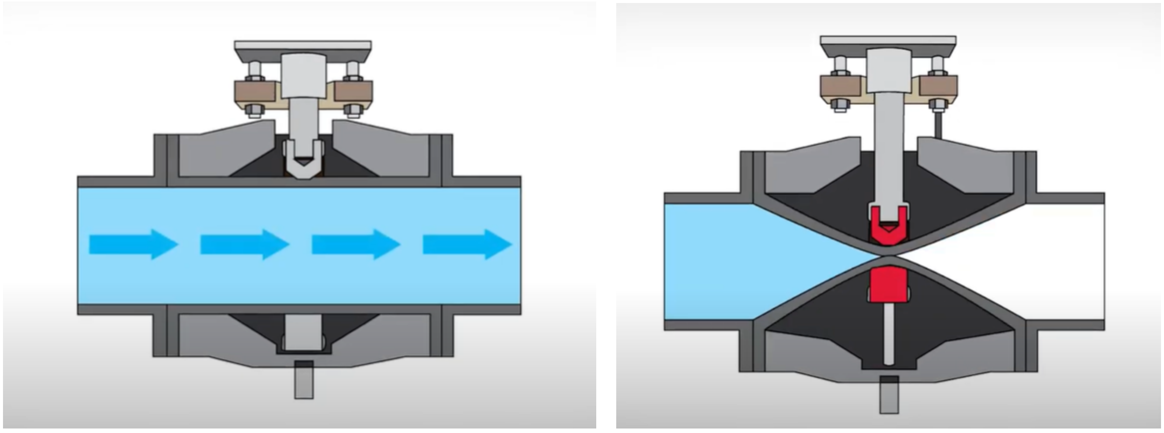
The proposed design concept should address the issues in DeLaval's existing milking systems. The new concept should be designed to eliminate the vacuum drop at the cluster while still considering the stakeholder requirements, found in Section 1.3. In this chapter, several concepts are discussed and evaluated.

The selection of a valve is limited by the requirements put forward by the stakeholders. **SR 6** states that all newly designed equipment used in the solution must fulfill food contact regulations. The food contact regulations taken into consideration are the ISO-standard 5707:2007. In practice, this means that the valve must ensure adequate volume for circulation. Therefore, the selected valve should not have small chambers or internal parts which could trap milk. Additionally, the material in contact with the milk must be food-safe and resistant to milk fat and disinfectant. There are also restrictions on the material's surface roughness and durability to temperature and pressure.

3.1 Design Concept 1 - Pinch Valve

The functionality of a pinch valve can be seen in Figure 3.1 where a) shows the pinch valve in its open state and b) its closed state. Pinch valves are generally used for viscous and lumpy fluids[26], it might therefore not work as desired with milk as a medium. Pinch valves are however commonly found in the food industry. As shown in Figure 3.1, only the sleeve itself is in contact with the flow medium and thus many potential problems with food-contact regulations can be avoided. Another benefit of this solution is that the pressure drop over the valve is low due to the fact that the flow is completely unimpeded when the valve is completely open.

Although there are some commercially available pinch valves that can be controlled using either vacuum or electronics, there are some concerns regarding the price of food-safe versions. The alternatives available to buy either fail to specify a price, and are therefore assumed to be expensive, or simply are too expensive. No budget has been specified, but the consensus is that the price should be moderate. Therefore, constructing a custom pinch valve might be necessary in order to both have food-safe materials and the sought-after ability to control, i.e. using a proportional solenoid to regulate the flow by clamping the tube.



(a) Actuator released, valve open. (b) Actuator applied, valve closed.

Figure 3.1: Pinch valve mechanism.

3.2 Design Concept 2 - Solenoid Diaphragm Hybrid

As described in Section 2.1, the current commercially used valve in DeLaval's system is a diaphragm valve. The valve is opened and closed using a vacuum signal that pulls the membrane away from the opening, allowing fluid to flow through the valve. This signal is slow and can be hard to control accurately enough for a regulator to be effective. The idea of a solenoid diaphragm hybrid valve is to combine an electronically controlled proportional solenoid with the already existing diaphragm valve and use the solenoid instead of a vacuum source for actuation of the diaphragm, see Figure 3.2. The benefits of using a solenoid are primarily the actuation speed and retraction precision. Using a regular solenoid valve without the food-safe property of the diaphragm valve is not suitable for this type of application. The commonly used solenoid valves have confined spaces for sand and dirt to get stuck, and are consequently more difficult to clean. In this hybrid alternative, the membrane that separates the solenoid piston from the milk maintains the food-safe quality of the diaphragm valve commercially in use today. The major problem with this design is that the piston needs to be attached to the membrane in order to be able to actuate the valve.

Another possible solenoid/diaphragm hybrid solution is to use the solenoid for a controlled inlet of air. By making an inlet on top of the valve and letting the piston of the solenoid seal/open the inlet, the airflow could be controlled. Applying a constant vacuum and letting the solenoid control the effect of the vacuum on the membrane, could result in a faster on/off function of the valve. However, this solution possesses the same binary actuation characteristic as is sought to be replaced by proportional actuation in order to achieve more accurate control.

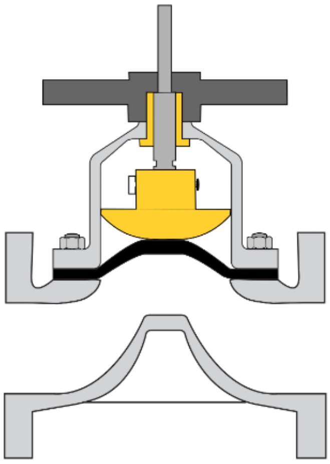


Figure 3.2: Solenoid diaphragm hybrid.

3.3 Sensor Placement

Any solution will utilize pressure sensors. One of the sensors will be positioned just below the cluster since this is where the vacuum is to be regulated. There will be two pressure sensors in the milk line, positioned at different distances from the valve. These will create a mathematical model of how the readings differ depending on sensor placement. The one furthest away from the cluster will then be used as input for the control system.

The ceramic pressure sensors will be fitted in the milk line with a modular solution using a custom-built housing. This allows the sensors full access to read the vacuum levels while causing as little disturbance in the system as possible in addition to avoiding any leakage. To achieve this, the housing will be a 3D-printed part that will easily be attached to tubes on both ends. The inside will be cylindrical to cause as little disturbance as possible to the flow and have a cutout for the sensor in the middle, see Figure 3.3.

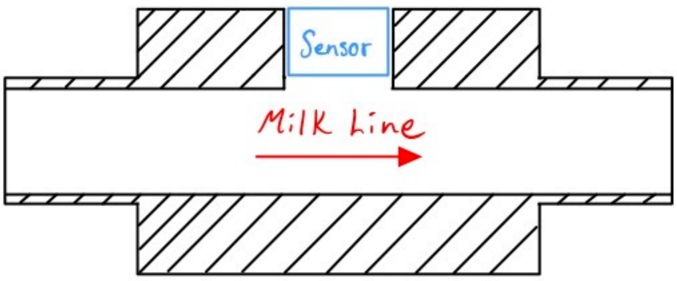


Figure 3.3: Sensor housing.

3.4 Evaluation

In order to evaluate the design concepts discussed in the previous section, a design evaluation matrix was made in which each criterion of the concepts is weighted and scored from 1-5. This helped the process of choosing which concept to realize and prioritize. See Table 3.1.

Criteria		Concept(1-5)		
	Weight(1-5)	Pinch	Hybrid	Current
Ease of implementation	5	3	3	4
Cost	3	2	3	5
Maintenance cost	3	3	4	3
Food safety	5	5	3	1
Easy to control	3	4	2	4
Easy to clean	4	5	5	3
Future expandability	1	5	4	1
Edge case function	3	3	1	3
Total(Weight×Concept)		101	84	83

Table 3.1: The evaluation assessment.

Where pinch represents the concept utilizing a pinch valve, hybrid the concept with a solenoid/diaphragm hybrid and the current solution as the solution that is in use today.

The most prominent concept turned out to be the pinch valve. It scored the highest in the criteria that were considered most important and thus it was the main priority concept of the project. The current solution is obviously not satisfactory, so it was disregarded completely.

Chapter 4

Method

This chapter describes how the project was approached. This includes a timeline, a work arrangement section, a risk analysis and a section about ethical approach.

4.1 Timeline

During the spring semester, a literature review was conducted and draft designs were made to be evaluated. This was finished by early June. At the start of the fall semester in late August, the building of the test rig begun and the ordered components from DeLaval arrived as planned. The vacuum pump arrived in early October, which delayed testing and validation of the test rig. Once the test rig was set up it was verified in parallel with designing the pinch valve. The deadlines for the tasks handled during this project are displayed in Table 4.1. A more detailed time plan with a Kanban board can be found in Appendix B.3.

Task	**Start Date**	**Finish Data**
Order parts	Late June	Mid September
Transport parts	Mid August	Early October
Build test rig	Early September	Mid October
Verify the test rig	Early October	Late October
Manufacture the designs	Mid September	Late November
Implement the solution	Mid October	Late November
Controller system finalized	Late October	Early December
Finalize the solution	Late November	Early December

Table 4.1: Project timeline.

4.2 Work Arrangement

The project group consisted of eight members. During the spring semester, the structure of the team was for the most part a single unit. To make sure everyone got a good understanding of the given task, the group had a lot of meetings with the agenda of discussing the problem and possible solutions. During research, the team was divided into smaller groups to find papers on research topics. The project leader for the spring semester was Samuel Stenow and this role rotated to Axel Sernelin for the fall semester.

To ensure finishing the project on time with sufficient quality, the team created a Kanban board to keep track of all tasks. The team held meetings with the stakeholders and the coach at least once a week. Weekly reports were written to prepare the stakeholders and the coach for these meetings.

The project management method used by the team was dividing the work into teams responsible for completing various tasks, such as test rig construction, physical design, software development and controller design. This is illustrated in Figure 4.1.

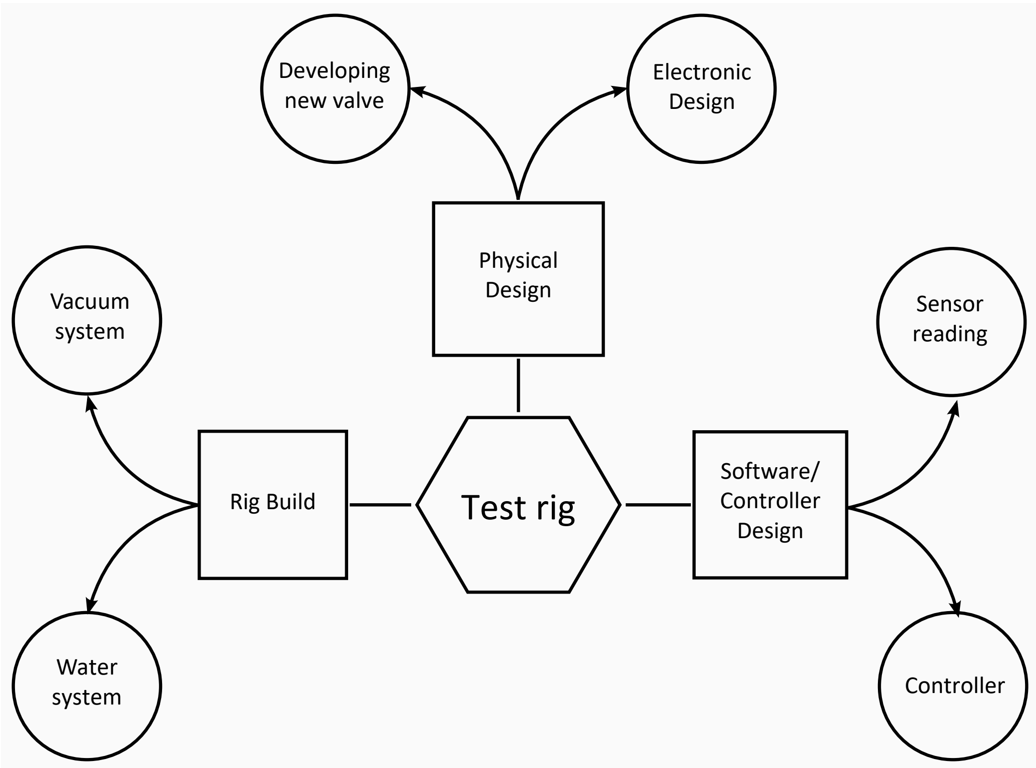


Figure 4.1: Visualization of work structures.

4.3 Risk Analysis

This risk analysis was done following a similar method as the Project Management Institute[30]. It begins with dividing the risk factors into four different categories, as shown in Table 4.2.

Risk Category	Extended categories
Technical	Requirements, Technology, Interfaces, Performance, Quality, etc.
External	Customer, contract, Market, Supplier, etc.
Organizational	Project Dependencies, Logistics, resources, Budget, etc.
Project Management	Planning, Schedule, Estimation, Controlling, Communication, etc.

Table 4.2: Four risk categories.

The Risk exposure or risk score is then calculated by multiplying the impact rating with the highest risk probability according to to Figure 4.2. The risk with the highest exposure score should be the category that needs the most attention from the project group.

		Probability			
		1 = high (80% < x < 100%)	2 = medium high (60% < x < 80%)	3 = medium low 30% < x < 60%	4 = low 0% < x < 30%
Impact	A=high (Rating 100)	(Exposure - Very High) (Score 100)	(Exposure - Very High) (Score 80)	(Exposure - High) (Score 60)	(Exposure - Moderate) (Score 30)
	B=medium (Rating 50)	(Exposure - High) (Score 50)	(Exposure - Moderate) (Score 40)	(Exposure - Moderate) (Score 30)	(Exposure - Low) (Score 15)
	C=low (Rating 10)	(Exposure - Low) (Score 10)	(Exposure - Low) (Score 8)	(Exposure - Low) (Score 6)	(Exposure - Low) (Score 3)

Figure 4.2: Impact-probability matrix.

The risk assessment on a few common or plausible risks can be found in Appendix B.1.

4.4 Ethical Approach

Throughout this project, multiple criteria have been considered to ensure ethically valid research. The results of the research are accurate, reliable and presented transparently. The data and results have not been fabricated, altered, or partially hidden in any way. Methods used to analyze the data have been transparently presented and the analysis of the results is appropriate and unbiased. The work is original, and the contribution of others has been properly acknowledged in the form of proper referencing.

The research was conducted in a manner that ensured the cow's well-being. Namely, a test rig was used which negated the need for testing on live animals. Moreover, the materials used were chosen carefully to avoid contaminants and diverse debris. Food safety and compliance were a top priority for the research team. The list of approved materials was provided by the case company that has been long established in the European food industry. The confidentiality of the involved parties has been respected. Any documents, figures, results, and information by the stakeholders have been kept within the group in a disclosed location out of reach of others. Any form of publication or documentation has been consented to by the stakeholders beforehand. There has been no conflict of interest, including financial and personal relationships, that affected the research.

Optimizing the control of a milking machine can benefit farmers in several ways. By ensuring that the cows are not subjected to unnecessary discomfort or pain during the milking process, it can help to improve the welfare of the animals, which is a key concern for many farmers. Food-safe contact is of great concern to avoid contamination of the milk. Using food-safe materials and shortening the milking time, leads to a minimized environmental impact of the milking process.

Chapter 5

Implementation

This chapter gives a detailed description of how the team has manufactured, implemented, and integrated the components to meet the requirements.

5.1 Test Rig

A flow chart of the test rig layout can be seen in Figure 5.1 and the full material list can be found in Appendix B.2.

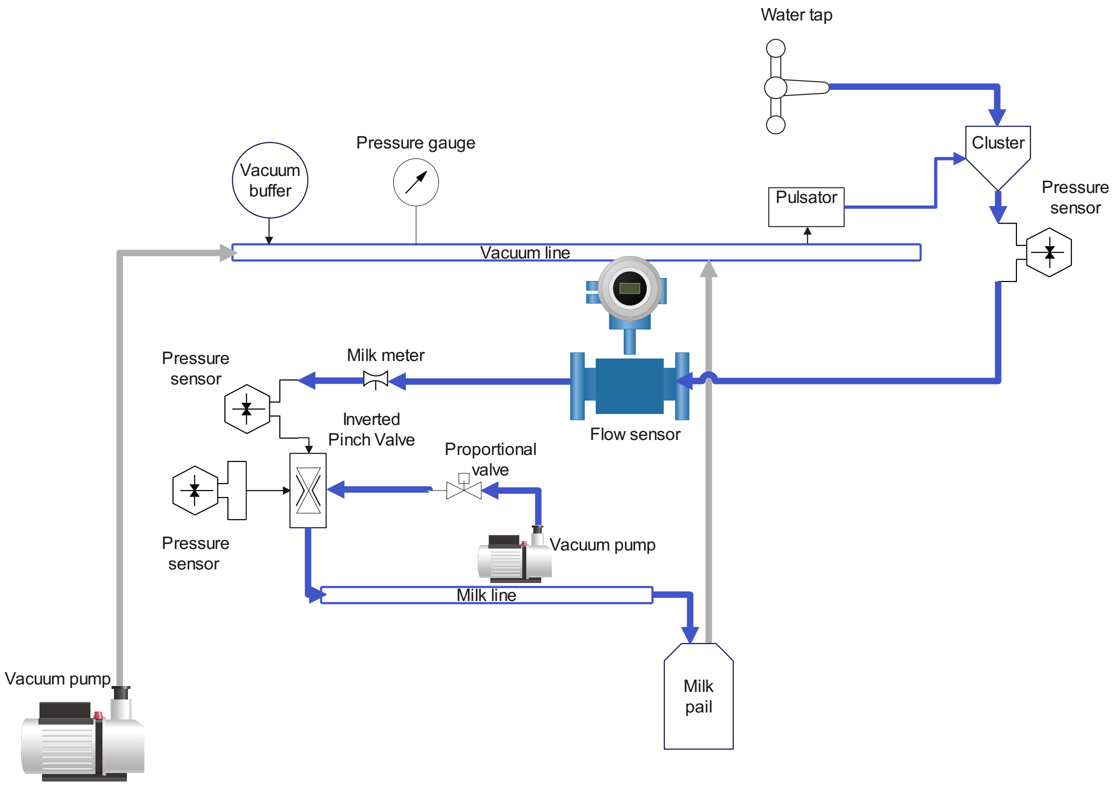


Figure 5.1: Flowchart of the test rig. Made in EdrawMax.

The vacuum in the system was generated from a vacuum pump which was connected to the main vacuum line. To add stability to the vacuum level in the system, a vacuum buffer was connected to the vacuum line. An analog pressure gauge was used to read the vacuum level to easier calibrate the vacuum pump to reach the desired level of vacuum in the system. The pulsator that generated the squeezing motion on the teat cups was connected to the vacuum line. The end of the milk line was also connected to the vacuum line through the milk pail, which generated a vacuum in the milk tubes.

The water, which replaced the milk, was supplied to the system from a tap that was manually turned to regulate flow. The water was divided into the four teat cups on the cluster. Directly below the cluster, a pressure sensor was placed to measure the suction in the cluster. The water then to flowed through the flow sensor and the milk meter. Just before the inverted pinch valve, a pressure sensor was placed, which was used as a reference for the controller. The inverted pinch valve was equipped with a pressure sensor to measure its internal pressure in the chamber. The vacuum inside the chamber was generated by an additional vacuum pump and regulated electronically with a proportional valve. After the valve, the water flowed through the milk line and ended up in the milk pail.

Milk Divider

To be able to supply all four teats with equal amounts of water, a water divider was designed and 3D-printed. The hose coming from the water tap was connected to the top inlet with a hose clamp. The four teat cups were then connected with a small short piece of tube each. The CAD design can be found in Appendix A.2.

Water Flow Meter

In order to conduct flow measurement in the system, and use it to indicate the relation between the flow rate and vacuum drop, a water flow meter was used. An inline model flow meter, which includes connectors to the upstream and downstream pipes, was chosen. The flow rate was also later used in the estimation of cluster pressure in combination with the pressure sensor placed just before the inverted pinch valve.

Vacuum Source

Two vacuum pumps were used. One was used as a supply to the system and was set to 55 kPa vacuum in accordance with **SR 3**. The other vacuum pump was used to generate vacuum in the chamber of the inverted pinch valve.

Proportional Valve

To be able to control the vacuum inside the inverted pinch valve chamber to a specific level, a PWM-controlled proportional valve was used. This made it possible to alter the vacuum level proportionally to an applied 24V PWM signal. The outlet was directly connected to the chamber of the inverted pinch valve. An image of the proportional valve can be seen in Appendix D.8.

5.2 Additive Manufacture

All the components manufactured by the team were made out of PLA plastic using an Ultimaker 2+ Connect 3D printer. The nozzle size was 0.8mm, the layer height was set to 0.2, the infill density was 100 percent with a grid pattern, the print speed was set to 60 except for the initial layer speed that was set to 30, support was used for 80 degrees overhang and lastly the brim setting was used. The nozzle and print bed temperatures should be set according to the instructions on the PLA material spool instructions. The temperature settings used for this project's prints were 220 degrees Celsius for the nozzle and 60 degrees Celsius for the print bed.

5.3 Inverted Pinch Valve

To deal with the issue of controlling a valve in a food-safe way with no complex internal geometry, it was concluded that a type of pinch valve would be most suitable. See Section 2.3. The conventional pinch valve used in high-pressure systems would not work in a low-pressure system due to its self-collapsing behaviour. However, with a few alterations, such a valve can be made applicable in a low-pressure system. In a low-pressure system, the sleeve will be normally closed, see Figure 5.2b. A pressure deficit between the inside and the outside of the sleeve causes it to collapse when $P_s < P_c$, cutting off the flow, see Figure 5.3. Since the chamber has atmospheric pressure by default, and there is a lower pressure in the sleeve, the sleeve is normally closed. The opposite is true for a pinch valve designed for high-pressure systems, which use a mechanism exerting force on the outside of the sleeve in order to cut off the flow. To make it work in a low-pressure system, a vacuum pump was used to decrease the pressure in the chamber, resulting in the reverse effect. In other words, this will open the sleeve, increasing the flow because $P_s > P_c$. See Figure 5.2a.

(a) (b)

Figure 5.2: a) Cross-sectional view of the inverted pinch valve when vacuum is applied to the chamber. b) Cross-sectional view of the inverted pinch valve when there is no vacuum applied to the chamber. Made in Solid Edge and rendered in KeyShot.

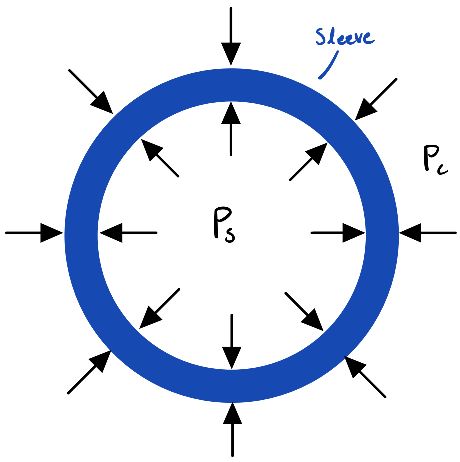


Figure 5.3: Illustration of the pressure difference inside and outside of the sleeve.

The final design of the inverted pinch valve can be seen in Figure 5.4. The chamber was made out of PLA plastic and manufactured using a 3D printer. It consists of two parts clamped together with an O-ring using four M6 bolts and nuts, see Figure 5.5. The chamber has four in-/outlets. Milk flows from the milk line into the valve on the left side, through the thin sleeve, and then out on the right side. The smaller inlet on top is connected with a thin tube to a vacuum pump via a proportional valve. The larger outlet on top is for connecting a pressure sensor to read the current pressure in the chamber. The outer diameter of the connection pipes for the milk line and sleeve is the same as the inner diameter of the sleeve, causing a fairly tight seal. The sleeve was however also glued on with epoxy to establish a secure seal.

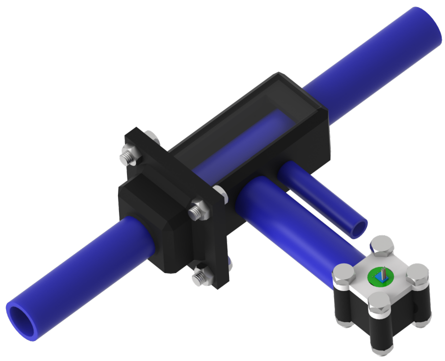


Figure 5.4: Assembled CAD design of the inverted pinch valve. Made in Solid Edge and rendered in KeyShot.

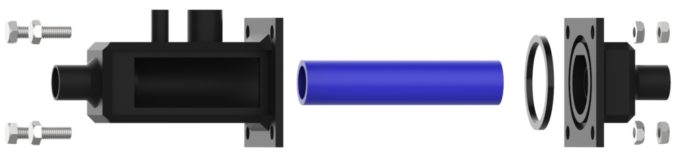


Figure 5.5: Exploded view of the inverted pinch valve. Made in Solid Edge and rendered in KeyShot.

5.4 Sensors

Design

For the pressure sensors to be properly integrated into the system, a housing was designed following the concept discussed in Section 3.3. It is illustrated in Figure 5.6a. The cross-section shown in Figure 5.6b further details the fastening of the sensor to the housing. The sensor rests upon an O-ring and is pushed down by the top cover which in turn is secured to the structure using four M6 bolts and nuts. The inner diameter of the passage was chosen to be the same as the connecting tubes in order to make a more homogeneous transition from tube to sensor. An exploded view can be seen in Figure 5.7. The corresponding data sheet for the pressure sensors can be seen in Appendix A.3.

(a) (b)

Figure 5.6: (a) Assembled final CAD design of sensor housing. (b) Cross-sectional view of the sensor housing. Made in Solid Edge and rendered in KeyShot.

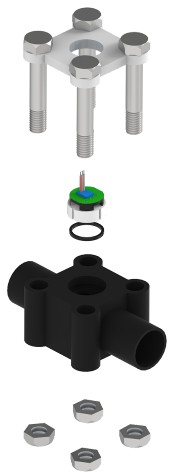


Figure 5.7: Exploded view of the sensor housing. Made in Solid Edge and rendered in KeyShot.

Placement

TR5 states that the design should be robust enough to withstand a harsh environment. This makes it more sensible to design the system such that a sensor at the cluster is not needed. The reason for this is that direct measurement at the cluster is not a robust solution due to its vicinity to the cow. Hence, the proposed implementation only used the sensor at the cluster for validation rather than control, and should not be used in a commercial application. The control sensor was instead placed further down the milk tubes from the cow, after the flow meter, but before the inverted pinch valve. It was placed before the pinch valve in order to have fewer disturbances affecting the pressure at the measuring point, making it more similar to the pressure at the cluster.

Cluster Estimation

A function predicting the built-in vacuum drop, combined with a Kalman Filter, was utilized to estimate the state at the cluster based on the measurement closer to the tube end. Deriving some governing equations for the milking system would be tedious since it contains a two-phase transient flow and many flexible components. Instead, the relation between vacuum drop and water flow is linearly fitted to propose an easy estimation.

5.5 Cascade Controller

When multiple sensors are available for measuring conditions in a controlled process, a cascade control system can often perform better than a traditional single-measurement controller. The system consists of a primary and secondary controller. A primary or master controller generates a control effort that serves as the setpoint for a secondary or slave controller. That controller in turn uses the actuator to apply its control effort directly to the secondary process. The secondary process then generates a secondary process variable that serves as the control effort for the primary process.

As shown in Figure 5.8, both loops employed PID controllers. The inner loop controls the inverted pinch valve chamber pressure, which was utilized as a control effort for the internal sleeve pressure. It generates a PWM signal to control the solenoid proportional valve. The outer loop contains the inner loop, the inverted pinch valve plant, a Kalman filter, and a linear approximation block. It feeds back the end sensor reading through the Kalman filter and approximation blocks, whose functions are illustrated above, to estimate the current state of the cluster pressure.

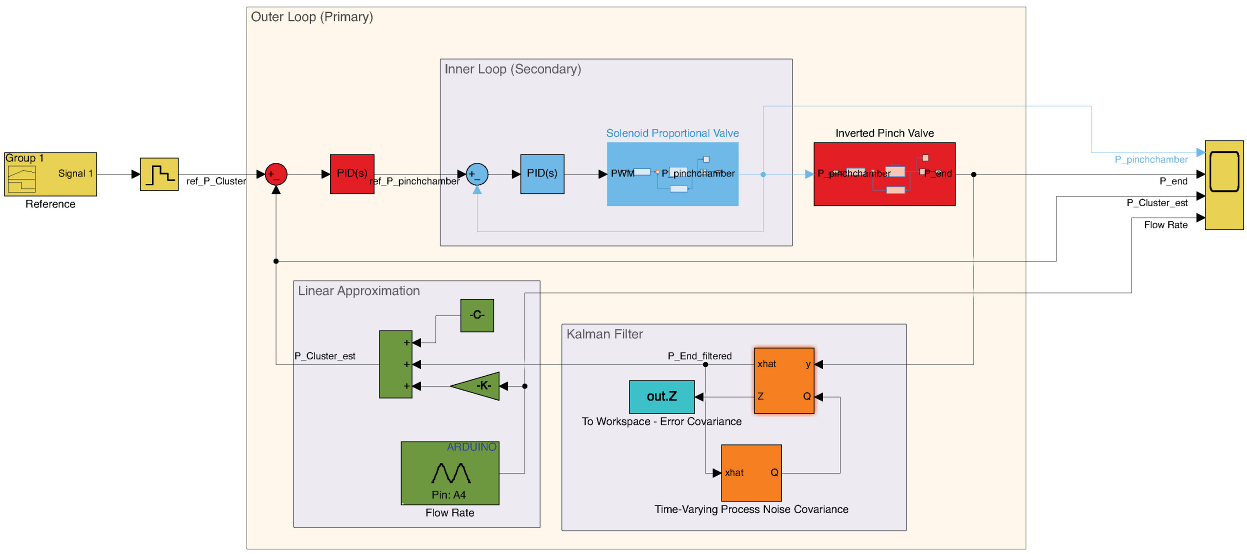


Figure 5.8: Cascade control system. Made in Simulink (MATLAB).

5.6 Software Development and Electrical Design

One program and one script were developed and implemented: one in Arduino for valve control and the other in MATLAB to read and plot sensor data in real-time. The codes are found in Appendix A.6 and A.5.

For the proportional valve, a driver circuit was created to control it with a PWM signal from the microcontroller. A circuit diagram of all the electronics can be found in Appendix E.

5.7 Verification

Several tests were conducted to know the limitations of the test rig as well as to verify that the test rig is a reasonable representation of a milking system. First and foremost, DeLaval's current valve solution was tested in terms of pressure drop over the valve itself and vacuum drop at the cluster as a result of different flow rates. The collected data was then compared to data collected by DeLaval on their test rig. Thereafter, the inverted pinch valve was put through the same types of tests. The following tests were conducted on the inverted pinch valve: pressure drop over the valve itself without any control and the valve completely open, pressure drop at the cluster without any control and the valve completely open, pressure drop at the cluster with control with a constant reference and a varying reference and lastly, a teat slip edge case test. Note that when testing DeLaval's current valve solution, the inverted pinch valve was simply removed and replaced with the current valve, no other alterations were made to the system.

Chapter 6

Results

In this chapter, all test results are documented and presented. This includes experiments conducted to verify and validate the function of the units and the entire system. Pictures of the test rig and the inverted pinch valve can be seen in Appendix D.

6.1 Controller Parameters

The PID controller parameters for the inner- and outer loop can be seen in Table 6.1.

Loop	K_P	K_I	K_D
Inner	0.25	$1e{-}11$	10
Outer	0.15	$2e{-}11$	1

Table 6.1: PID controller parameters.

6.2 Current Valve

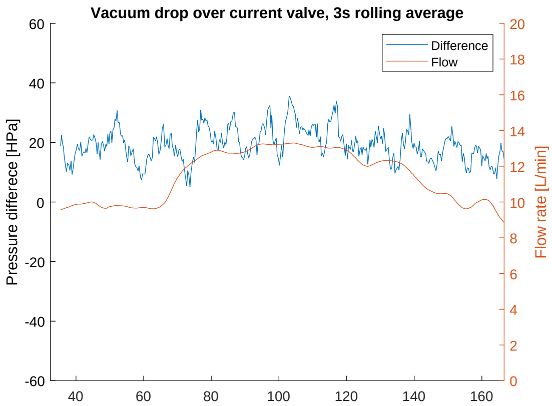
The following tests were conducted using DeLaval's current valve.

Vacuum Drop

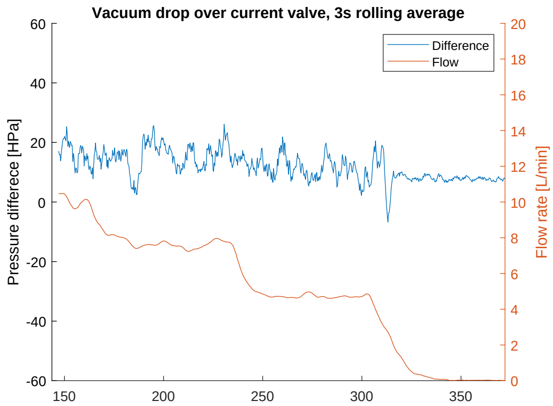
For this test, a sensor was placed before and after DeLaval's current valve. Results are shown in Table 6.2 and Figure 6.1.

System vacuum [kPa]	Flow rate [L/s]	Average vacuum drop [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	1,2	2,6	-0.7
55	10 - 14	1,9	3,6	0

Table 6.2: Vacuum drop over the current valve. Average vacuum drop for different flow rates with min and max readings.



(a)



(b)

Figure 6.1: Pressure drop over DeLaval's current valve for flow rate intervals of 0 - 10 L/min (b) and 10 - 14 L/min (a).

6.3 Unit Test

The test was conducted at different flow rates and a mean pressure drop was calculated for each flow rate.

Controller Design

The controller was built using an Arduino microcontroller, which means that the K_P (proportional) gain was fixed. However, the K_I (integral) and K_D (derivative) gains were based on the sampling time (T_s). The K_I gain was calculated as K_I times T_s, and the K_D gain was calculated as K_D divided by T_s. The values for I (the integral gain) and D (the derivative gain) are dynamic parameters that are affected by the sampling time T_s. For a demonstration of the PID controllers, a typical sampling time of $T_s = 1\,\text{ms}$ was selected to screen the step response of the inner and outer loop controller.

Linear Relationship

In order to explore the relationship between vacuum drop and flow rate, tests were conducted with flow rate as a step input while the inverted pinch valve was fully open. The flow rate was incremented and kept constant until the vacuum reached a steady state for each increment as shown in Figure 6.2.

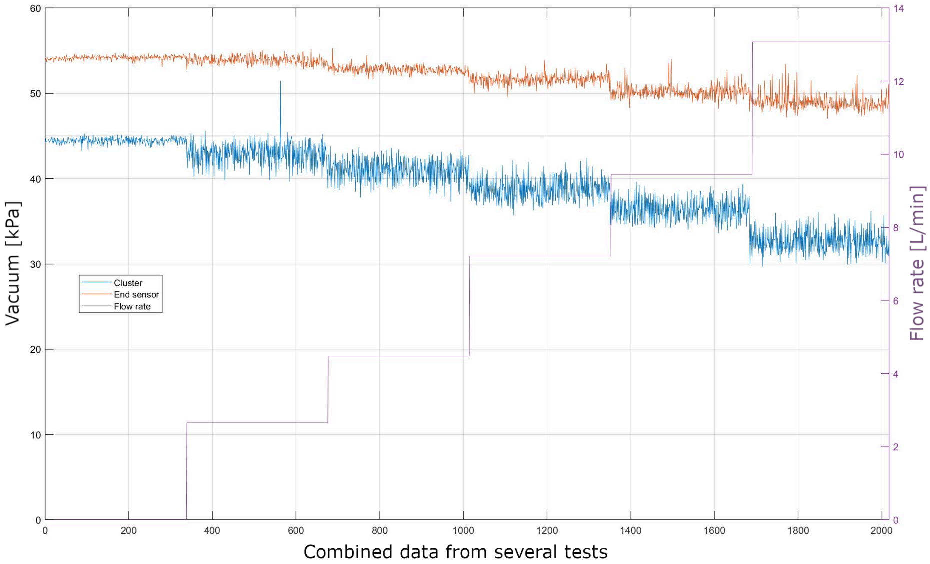


Figure 6.2: Combined data from several tests.

The difference between the sensors readings with respect to flow rate were logged and plotted to fit a linear curve. The resultant plot is shown in Figure 6.3 and the linear equation is $\Delta P = 5.15 * f + 2.76$, where f is the flow rate.

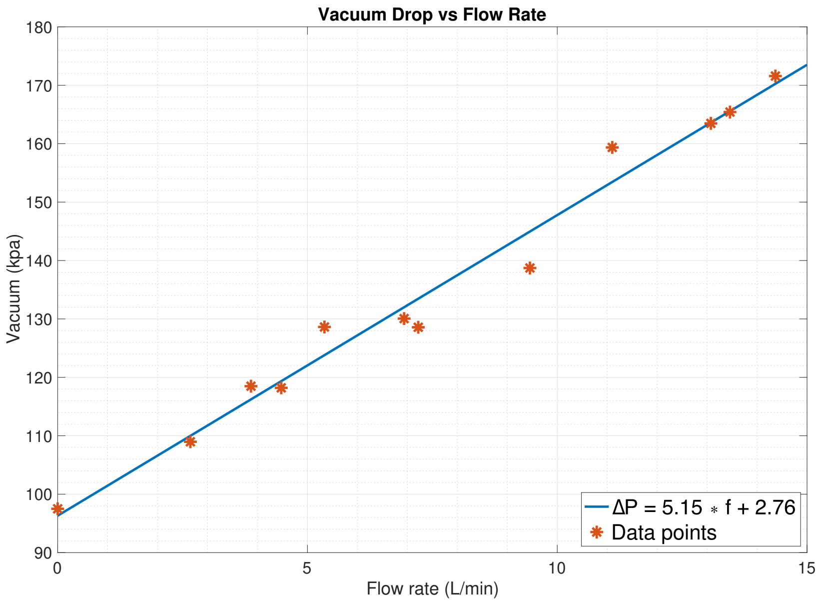


Figure 6.3: Linear fitting of test data for the vacuum difference between the cluster sensor and the controller sensor with the inverted pinch valve fully open.

6.4 Inverted Pinch Valve

This section covers the resulting performance of the inverted pinch valve. For the following figures, *Pinch* refers to the vacuum level in the chamber of the inverted pinch valve, *Controller Sensor* refers to the vacuum level just before the inverted pinch valve, and *Cluster* refers to the vacuum level at the cluster. All figures are displayed with a three-second rolling average.

Without Control

In this test, the pinch valve was fully open and no control was used.

System vacuum [kPa]	Flow rate [L/s]	Average vacuum difference [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	8,1	12,9	0
55	10 - 14	(-)0,15	8,7	-6,5

Table 6.3: Pressure difference between the cluster vacuum and reference level.

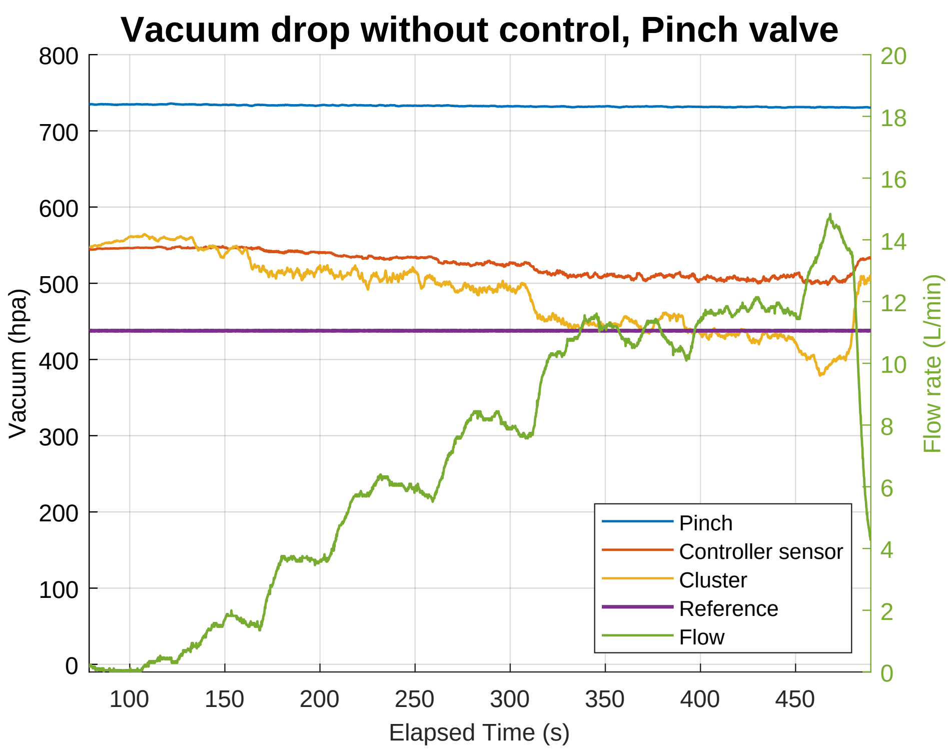


Figure 6.4: Vacuum level at the cluster for different flow rates without control. The inverted pinch valve is fully open.

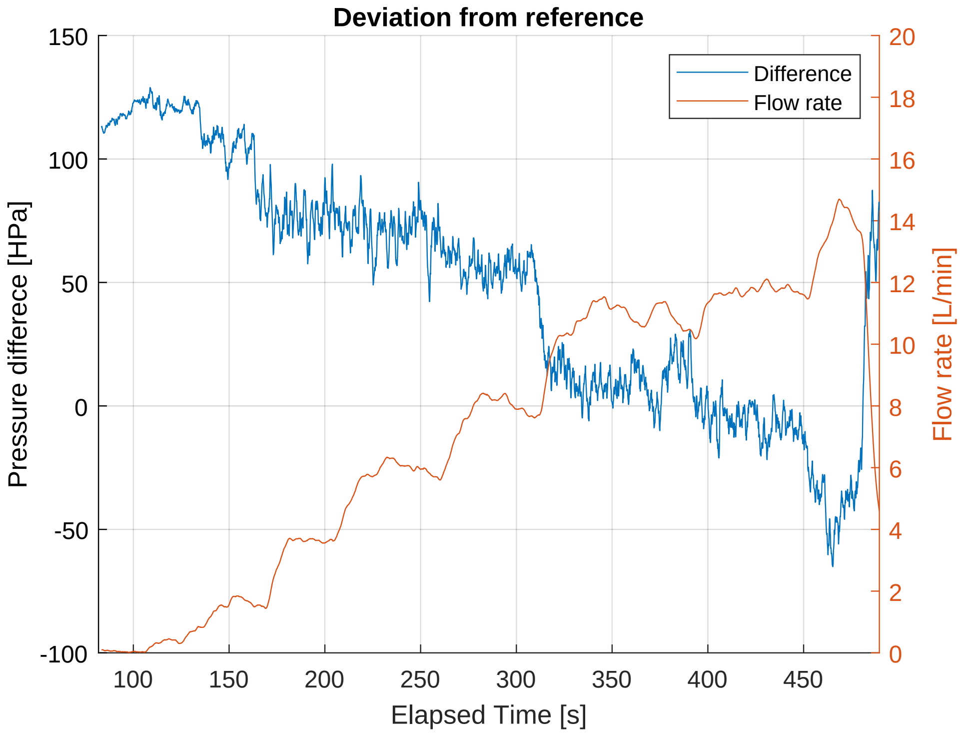
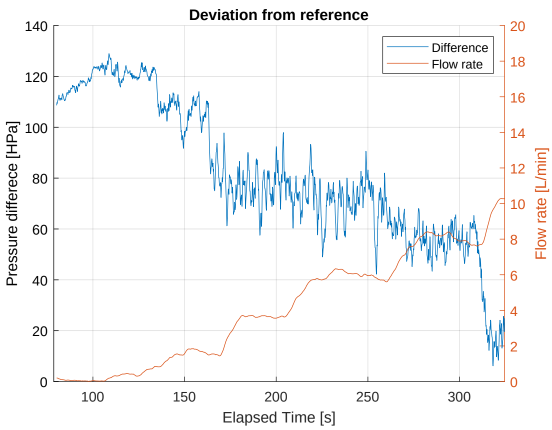
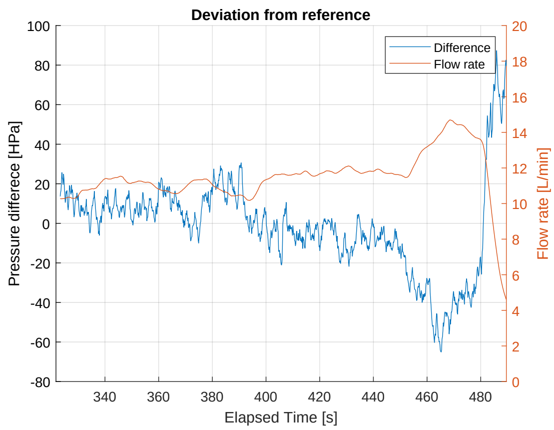


Figure 6.5: Pressure difference between the cluster vacuum and reference without any control and valve fully open.



(a) Pressure difference between cluster vacuum and reference at flows between 0-10L/min.



(b) Pressure difference between cluster vacuum and reference at flows between 10-14L/min.

Figure 6.6: Pressure difference between the cluster vacuum and reference for different flow intervals. No control and the valve fully open.

Constant Reference

In this test, the inverted pinch valve was regulated with a reference set to a constant level of 45 kPa vacuum.

System vacuum [kPa]	Flow rate [L/s]	Average vacuum difference [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	3,9	14	-7,3
55	10 - 14	(-)1,04	2,6	-5

Table 6.4: Pressure difference between the cluster vacuum and reference.

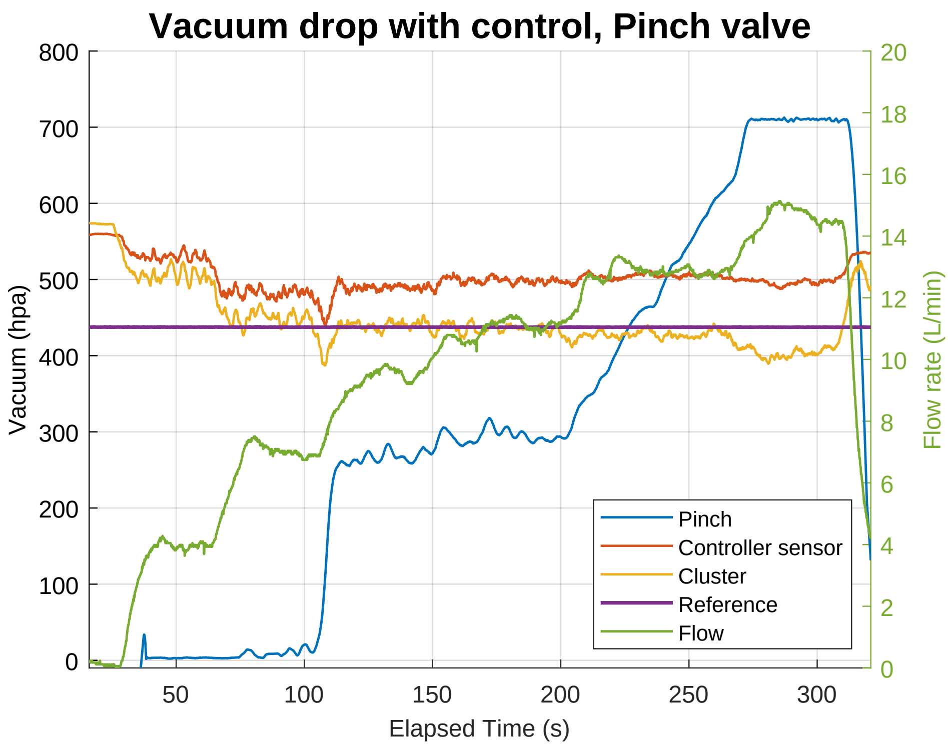


Figure 6.7: Vacuum level at the cluster for different flow rates with a constant reference set to 45 kPa.

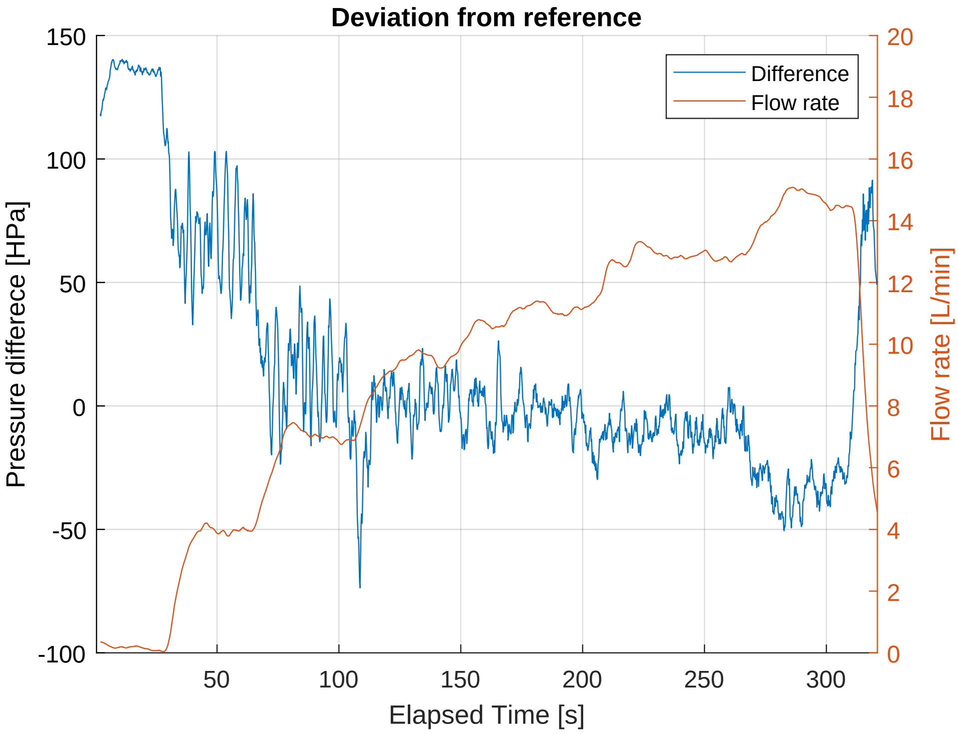
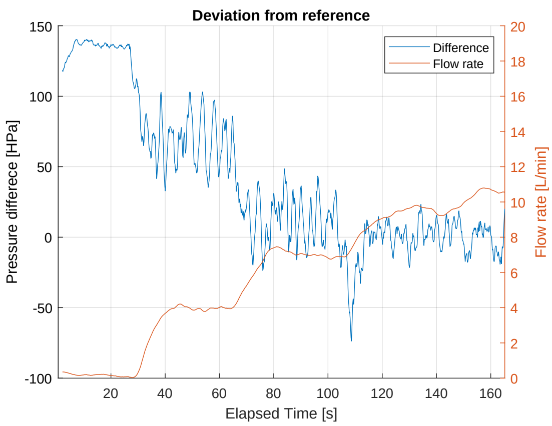
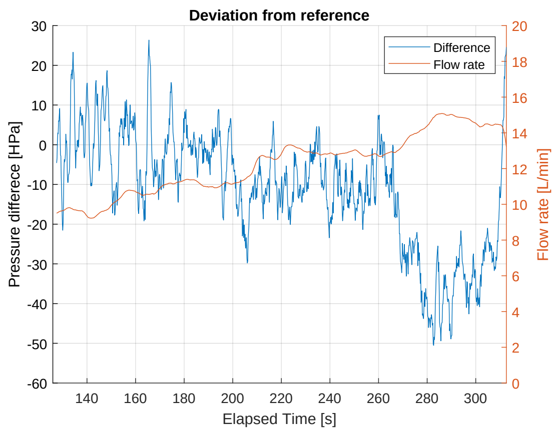


Figure 6.8: Pressure difference between cluster vacuum and reference for different flow rates.



(a) Pressure difference between cluster vacuum and reference for flow rates between 0-10 L/min.



(b) Pressure difference between cluster vacuum and reference for flow rates between 10-14 L/min.

Figure 6.9: Vacuum drop over the inverted pinch valve with associated flow ranges.

Varying Reference

System vacuum [kPa]	Flow rate [L/s]	Average vacuum difference [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	8	0,56	12,8	-5,4

Table 6.5: Pressure difference between the cluster vacuum and reference.

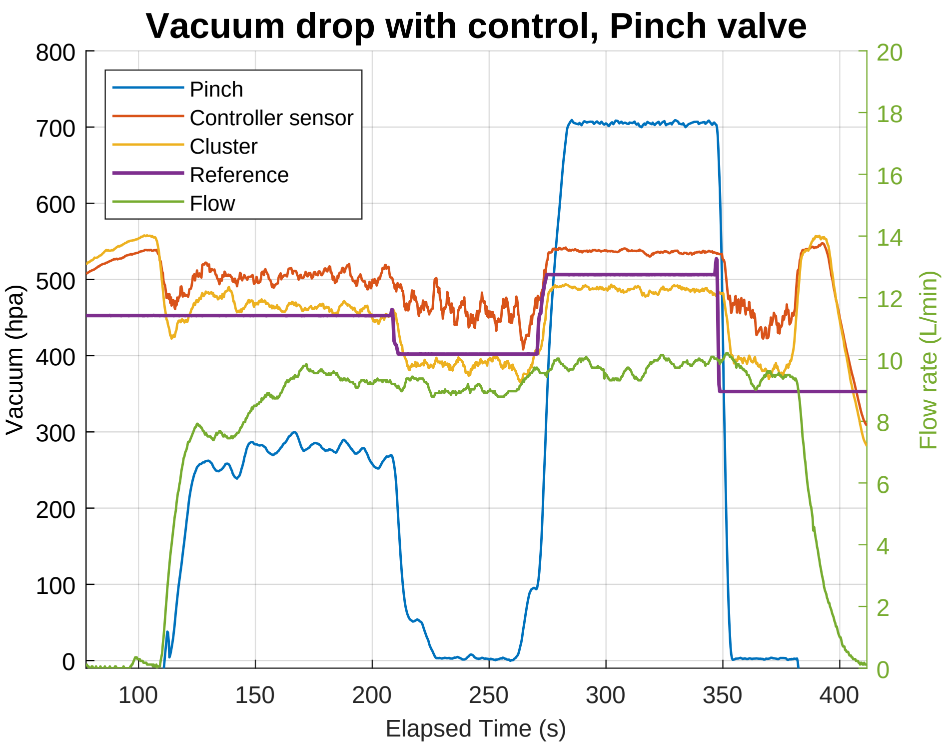


Figure 6.10: Vacuum level at the cluster with control and varying reference between 40-50 kPa.

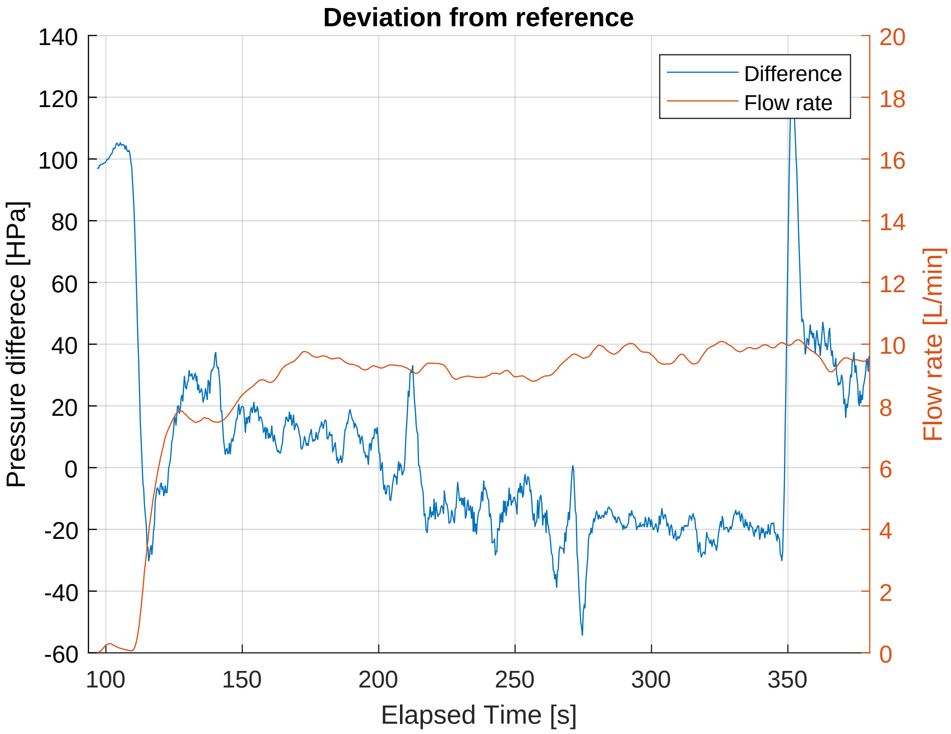


Figure 6.11: Pressure difference between cluster vacuum and reference with varying reference between 40-50 kPa and constant water flow.

Vacuum Drop

For this test, a sensor was placed before and after the inverted pinch valve while the valve was fully open. Three tests were conducted with different flow rate increments.

System vacuum [kPa]	Flow rate [L/min]	Average vacuum drop [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	0,96	4,9	-7,8
55	10 - 14	0,78	2,7	-1,4

Table 6.6: Test 1: Vacuum drop over the current valve. Average vacuum drop for different flow rates with min and max readings.

System vacuum [kPa]	Flow rate [L/min]	Average vacuum drop [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	1,4	5,5	-1,3
55	10 - 14	0,6	2,1	-1,5

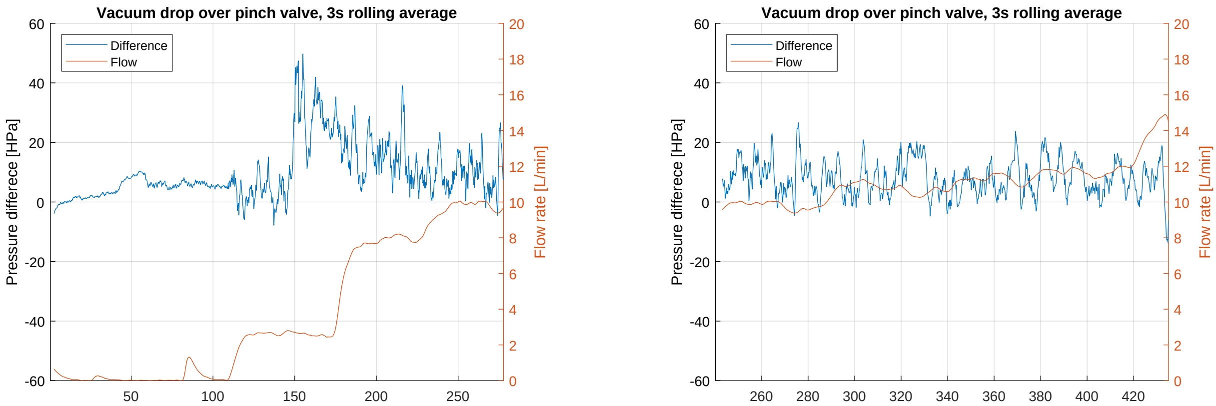
Table 6.7: Test 2: Vacuum drop over the current valve. Average vacuum drop for different flow rates with min and max readings.

System vacuum [kPa]	Flow rate [L/min]	Average vacuum drop [kPa]	Max oscillation [kPa]	Min oscillation [kPa]
55	0 - 10	1,5	2,9	-2,3
55	10 - 14	0,76	2,5	-0,73

Table 6.8: Test 3: Vacuum drop over the current valve. Average vacuum drop for different flow rates with min and max readings.

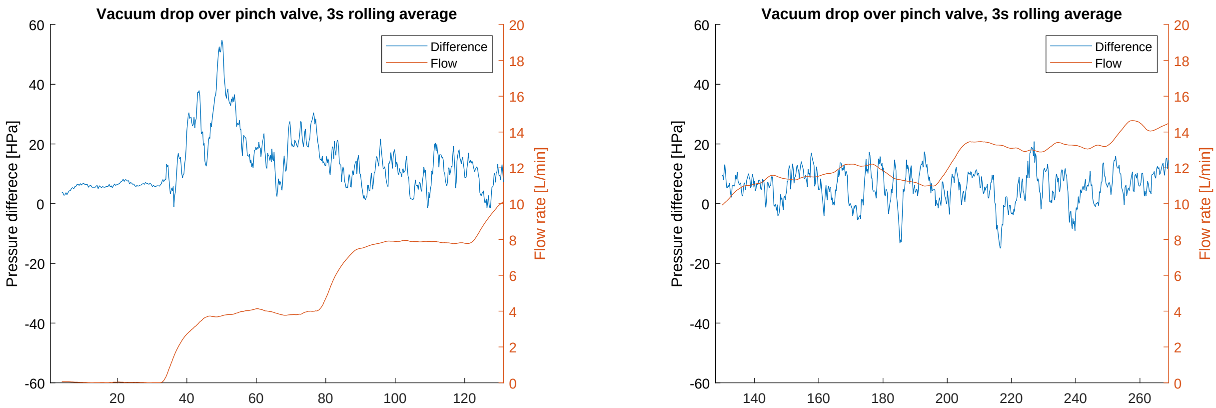
System vacuum [kPa]	Flow rate [L/min]	Average flow rate [L/min]	Vacuum drop [kPa]	Min-Max [kPa]
55	8,8 - 11,2	10,2	0,81	-0,46 - 2,7

Table 6.9: Vacuum drop over the pinch valve for an average flow rate of 10 L/min. Data taken from Test 1 seen in Table 6.6.



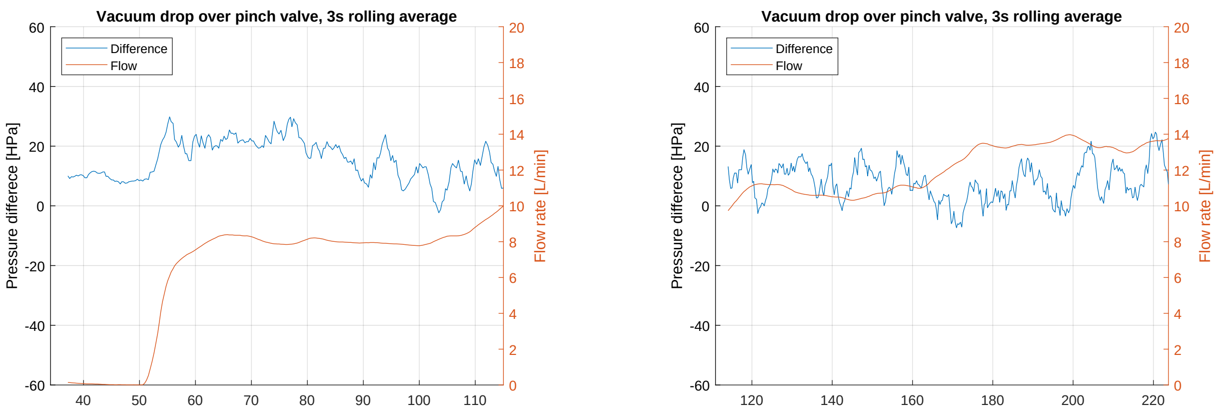
(a) (b)

Figure 6.12: Vacuum drop over the inverted pinch valve from Test 1 with associated flow ranges.



(a) (b)

Figure 6.13: Vacuum drop over the inverted pinch valve from Test 2 with associated flow ranges.



(a) (b)

Figure 6.14: Vacuum drop over the inverted pinch valve from Test 3 with associated flow ranges.

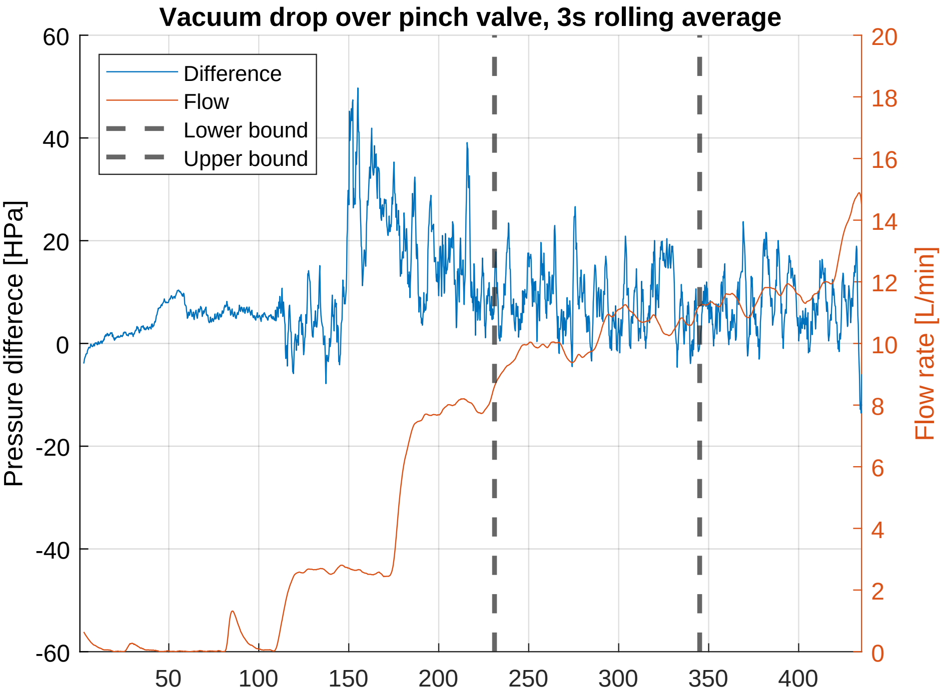


Figure 6.15: Vacuum drop over the inverted pinch valve during Test 1 for a specified range, used in Table 6.9. The dotted lines show the area where the average flow rate is approximately 10 L/min.

6.5 Edge Case Test

This section covers results from testing one of the edge cases defined in **SR 7**.

Teat Slippage

This test was done to mimic the situation where one teat cup of the cluster slips off the cow's teat during the milking process. This test was done at a constant flow rate of 8 L/min. The slippage was achieved by manually letting air in at one of the teat cups. The system vacuum was 55 kPa.

System vacuum [kPa]	Flow rate [L/min]	Average vacuum drop [kPa]	Vacuum drop [kPa]	Min-Max [kPa]
55	0-8	1,8	12,1	-12,3

Table 6.10: Pressure difference between the cluster vacuum and reference during teat cup slip test.

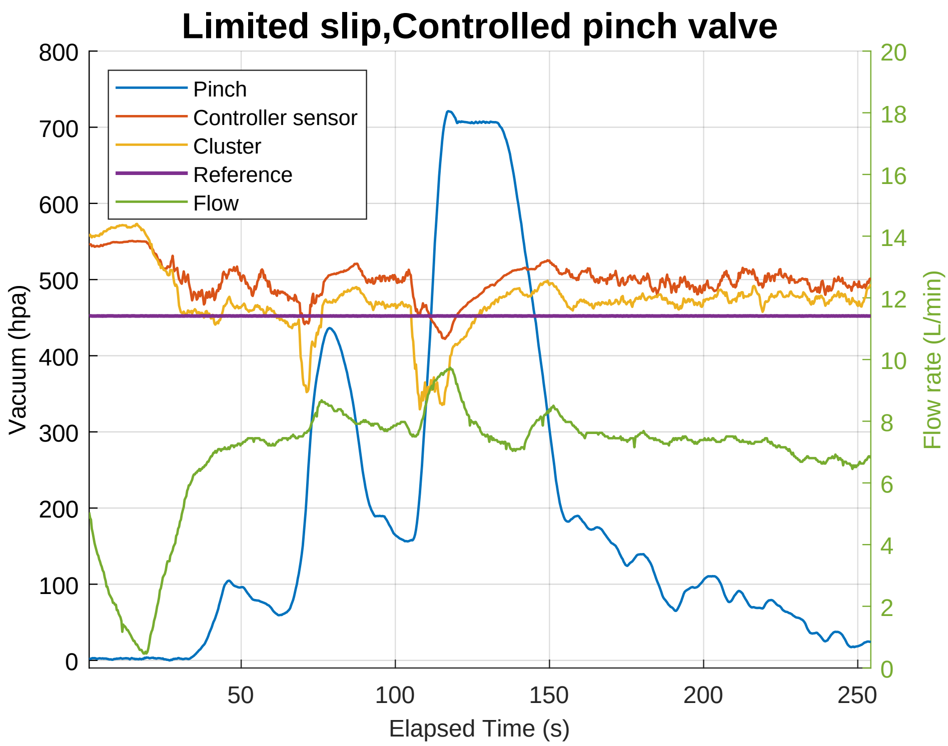


Figure 6.16: Emulated slippage of one of the teat cups with a constant flow of 8 L/min. Short slip after 75 seconds and a longer slip after 110 seconds.

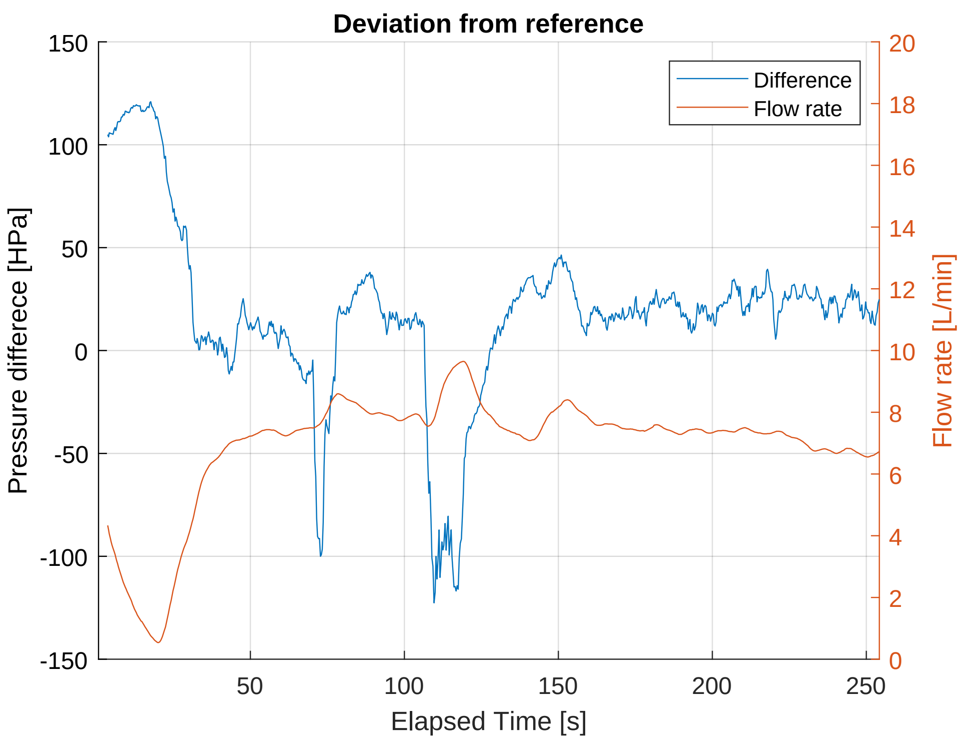


Figure 6.17: Pressure difference between the cluster vacuum and reference during teat cup slip test.

Chapter 7

Discussion and Conclusion

This chapter discusses and evaluates the results presented in the previous chapter. It also further explains how and why the results show an improvement compared to DeLaval's current solution. In addition, a brief conclusion is given by the end of this chapter.

7.1 Test Results

The results showed that by implementing a controller to regulate a pinch valve, the vacuum level at the cluster can be kept rather stable at a preset reference, see Figure 6.8. However, due to some limitations in the design, the valve is unable to completely close at low flow rates. This results in too high vacuum levels at those rates. This behaviour is explored more deeply in the sections below. This is the reason why the solution does not fulfill the requirements for vacuum losses with flow rates ranging from 0-10 L/min. For larger flow rates, the difference between the cluster vacuum and reference level is kept around 1 kPa, fulfilling the **TR2** requirement with some margin to spare.

The validation test was done by comparing the vacuum drop at the cluster as a result from different flow rates when using the inverted pinch valve with a fully open configuration, shown in Figure 6.2. The step-like vacuum drops suggested that the test rig was working as intended and the test rig was deemed adequate.

Edge Case

The teat cup slip edge case was selected to be investigated. When introducing slippage in a teat cup, a vacuum loss occurs. The controller tries to compensate for the sudden loss by changing the inverted pinch valve chamber vacuum. After some time, the vacuum level is back to normal. This process is illustrated in Figure 6.16. This however, is limited by the controller's inability to compensate for the large vacuum drop in the system's vacuum level. The whole system lost 10 kPa during this test because the vacuum pump can simply not compensate for this air leakage. With the use of a more powerful vacuum pump, the compensation should be quicker. The reasoning behind this statement is that the cluster vacuum can only be raised by opening the valve and allowing the system vacuum to drive it up. But if the entire system loses vacuum, this process is hampered and the controller becomes slower.

Controllable Range

After conducting all tests, a controllable range was observed. The cluster vacuum can be controlled between 40 - 50 kPa when the system vacuum is set to 55 kPa and the water flow rate is around 8 - 10 L/min. When the reference is set to 45 kPa, which is the optimum level, the cluster vacuum can successfully be regulated for flow rates between 6-12 L/min. This can be seen in Figure 6.8, displaying the results of a test with varying flows with the pinch valve actively regulating the cluster pressure.

The upper limit of the controllable range is limited by the system vacuum supply level. At high flow rates above 12 L/min, the inverted pinch valve is already fully open and can not regulate any further. This means that in order to regulate the cluster pressure for flow rates above 12 L/min, the system vacuum has to be set higher initially. This can be seen in Figure 6.8. The system supply vacuum was limited to 55 kPa according to **SR 3**. During an average milking session, the milk flow rate only reaches this high flow rate for a short period of time, meaning that improving and increasing the range's upper bound would only result in a small benefit.

The lower limit of the controllable range is currently limited to how tight the inverted pinch valve manages to close. The current configuration can be observed to always allow a small flow of water through the valve even when it is fully closed. At the start and end of a milking process, the flow will be in the range of 0 - 4 L/min.

Sensor Placement

The pressure sensor used by the controller, known as the controller sensor, was initially placed as far away from the cluster as possible. This was done in order to avoid any potential interaction with the cow, who has a tendency to kick off the milking cluster and stamp on the milk tube. Therefore, it was placed right before the valve which ended up being a good choice since it was able to notice pressure differences that occurred because of different flow rates. It should in theory be possible to move the pressure sensor even further away from the cluster as long as it is in the milk tube. The sensor needs to be able to detect the subtle changes in vacuum as a function of flow in order to estimate the vacuum level at the cluster, which is in turn used to regulate the system. If the sensor were to be moved, the linear equation derived in Section 6.3 had to be re-calibrated.

The flow sensor was placed in the middle of the system for ease of access but is subjectively not in a good spot since it would be right next to a cow in a real-world scenario. However, the flow sensor could very well be moved and potentially even removed completely. As shown in Figure 6.4 the vacuum drop at the cluster is proportional to the flow rate but also against the vacuum at the controller sensor. Implying that with enough knowledge about the system, one could calculate the flow rate and potentially even calculate the cluster vacuum straight away without any knowledge of the flow rate, removing the need for the flow meter in its entirety.

Vacuum Drop

As shown in Table 6.4, the difference between the cluster vacuum and the reference was above 1 kPa for flow rates ranging from 0 - 10 L/min, not fulfilling **SR 4**. As can be seen in Figure 6.7, the valve can not regulate down the vacuum enough for it to follow the reference for flow rates below 6 L/min. The inverted pinch valve chamber control signal is zero vacuum i.e. atmospheric pressure, which means the valve is fully closed. It is not until the flow rate reaches above 6 L/min that the cluster vacuum drops down to the reference level. Above this flow rate, the valve then starts to regulate accordingly. For flow rates ranging from 10 - 14 L/min, the difference between the cluster vacuum and the reference was a lot smaller. Up until about 12 L/min, the inverted pinch valve can still regulate the pressure but as the flow rate reaches above 12 L/min the inverted pinch valve chamber control signal peaks.

As expected, the vacuum drop over the valve itself was very low due to the design of the valve. For low flow rates ranging from 0 - 10 L/min the vacuum drop over the valve averaged around 1 - 1,5 kPa for different test cases and is seemingly on par or slightly worse than the current design. If this is due to the valve itself or just the sporadic nature of the flow at these levels its hard to tell but the results are promising nonetheless. For flows ranging from 10 - 14 L/min, the vacuum drop over the inverted pinch valve was very small compared to the current valve. The tests results showed the average drop ranged from 0,5 - 1 kPa, which was expected since the valve is essentially a tube like any other milk tube in the system.

Lastly, since the test rig was supplied with water from a water tap, the flow rate was very hard to control and was rarely very stable. In order to know the average vacuum drop for a flow rate of 10 L/min, a range was selected from test 1 so that the average flow rate matched this number. The selected range is shown in Figure 6.15. Table 6.9 shows the results of this test with an average flow of 10,2 L/min resulting in a vacuum drop of roughly 0,8 kPa which fulfills stakeholder requirement **SR 1** of a max 1kPa.

Controller Design

According to pole placement theory, if the closed-loop poles for the position loop are sufficiently slower compared to the closed-loop poles of the velocity controller, which is fairly obvious in this system, then it is possible to use the simple model

$$y = \frac{1}{s}x, \tag{7.1}$$

where x is the inverted pinch valve chamber pressure, and y is the cluster pressure. The standard rule of thumb is that loops should be separated with a factor of 10 in frequency.

Despite the failed attempts to identify a model, thereby conducting the pole placement in a more accurate fashion, the K_P, K_I, and K_D terms of the two loops were tuned to a reasonable ratio so that the controller had a better performance.

A potential problem is that the cluster pressure controller may generate very large pinch valve chamber pressure references, which did happen during testing. Instead of merely generating the cluster pressure reference as a step, something smoother, such as a ramp or a low pass filter on the reference signal could have been considered.

7.2 Requirements Verification

As shown in Table 7.1, **SR 1**, **SR 2**, **SR 3**, **TR 1** and **SR 8** were successfully fulfilled as the newly designed inverted pinch valve achieves a pressure drop of less than 1 kPa at 10 L/min with the valve fully open in the test rig, with a low line configuration and a system vacuum of 55 kPa. .

SR 4 was partially fulfilled. **TR 2** was not achieved as the average vacuum drop was larger than the maximum 1 kPa required. **TR 3** was achieved as the average drop in vacuum was lower than 2 kPa.

SR 5, **TR 4**, **TR 5** was achieved as both the valve and sensor housing is designed to be modular and easy to clean as it has no small chambers or internal parts in which contaminants could be trapped. The designs are modular so the valve can easily be interchanged and it is robust enough to withstand water and dirt.

SR 6 is only considered to be partially fulfilled as the designs are geometrically food safe but the current prototype has been manufactured using non-food-safe material (PLA 3D-printing plastic). In a real application, the non-food-safe materials in contact with milk can easily be replaced with food-safe alternatives by manufacturing it in the same way as DeLaval's current valve.

SR 7 was fulfilled since **TR 7** could be tested and the controller could regulate in order to account for the disturbance with some minor problems discussed in the previous section.

Requirement	Fulfillment
SR1	Yes
SR2	Yes
TR1	Yes
SR3	Yes
SR4	Partially
TR2	No
TR3	Yes
SR5	Yes
TR4	Yes
TR5	Yes
SR6	Partially
SR7	Yes
TR6	-
TR7	Yes
TR8	-
SR8	Yes

Table 7.1: Table showing requirements and associated fulfillment. Refer to Section 1.3 for more details regarding the requirements.

7.3 Conclusion

The results show that it is possible to create an electronically vacuum regulated shut-off valve for milking systems. By implementing an inverted pinch valve controlled by a simple microcontroller, the vacuum level at the milking cluster follows a reference signal set to 45 kPa for flow rates ranging from 6 - 12 L/min with a minimal vacuum drop. Furthermore, by implementing some minor tweaks and changes discussed in previous chapters, it should be possible to extend the operational range and increase the performance of the inverted pinch valve.

Chapter 8

Future Work

So far in the project, some critical areas have been researched and several designs have been proposed and evaluated. In this chapter, limitations and directions for future research are addressed.

8.1 Overall System Improvements

The overall system improvements can be divided into three improvement areas: valve, test rig, and simulations.

Valve

A possible improvement of the valve would be to increase the controllable range. As mentioned in the discussion, the valve can not be controlled to reach a higher vacuum and compensate for the pressure drop at flow rates above 12 L/min without increasing the system supply vacuum. However, the lower limit of the controllable range could be increased by being able to close the valve fully. As mentioned in the discussion, the current valve can not be closed fully as a small water flow can always be observed. The sleeve used in this prototype is as described in Section 5.3, a piece of tubing from the milk line which in turn was sanded down to be thin enough to easily collapse by a pressure deficit inside in relation to the outside. The optimal thickness to achieve this was never tested thoroughly, which could possibly improve the results even more. It is suspected that a thinner sleeve would lead to a tighter seal and thus improving control at low flow rates.

There is no particular reason as to why the sleeve was designed to have the current length, but a longer sleeve could hypothetically improve how well it cuts off flow since the area of contact between both sides of the sleeve will be larger.

With more time and resources it could be possible to test out different materials that are more flexible or tolerable in terms of long-term use. The current material is not specifically made for elastic strain which could makes it unsuitable for long term use. The geometrical design of the sleeve could also be a factor that may change its performance. Making the sleeve thinner at some parts and thicker at other parts would change the way it forms/deforms which possibly could have a positive result on the performance of the inverted pinch valve.

Another factor that could potentially improve the valve is to increase the speed of the control vacuum signal to the inverted pinch valve chamber. This could be achieved by using a PWM valve (which regulates the pressure to the pinch valve), with support for a higher air flow rate than the one which was used. In combination with this, the tube from the PWM valve could have been shortened in order to decrease the total volume. This would mean that the valve could change its chamber pressure faster and thus respond faster to pressure changes in the system.

Test Rig

The test rig can be further improved in several areas.The water flow was hard to regulate with a manual water tap and this could have been replaced with an electric flow regulator to simplify the testing procedure. In this way, the flow could have be varied more continuously and the milking process replicated more accurately.

In the current configuration, the sensors have to be re-calibrated after changing their position in the system. The reading on the pressure sensors is affected by how hard the bolts have been tightened in the mountings and a future improvement could be to make them calibrate automatically.

Linear Model Calibration

If the inverted pinch valve were to be used in a real application scenario there has to be a way to calibrate the linear vacuum drop model. This model will vary depending on the length of the milk tubes, the number of components on the milk tube, the type of milk tubes, the type of cluster, etc. This means that when calibrating, a sensor has to be placed at the cluster to measure the drop while a cow is being milked. When this calibration is done and enough data to generate a linear model is collected, the sensor at the cluster can be removed. This calibration should be done in a controlled manner in order to avoid damage to cows nor equipment.

Simulation

Another improvement area is the simulation of the system. Currently, the system model relies on a linear interpretation the pressure drop between the cluster and the controller sensor. An improvement would be use a better model for approximating the pressure at the cluster. This could be obtained through system identification.

8.2 Field Test

As of the completion of the project, for practical purposes, the system has thus far only had to endure water. To ultimately validate the function of the regulating valve, testing it in the environment in which it is to be applied is crucial, meaning it should be tested by pulling milk from the udders of a real cow. The current state of the system offers the safety precautions needed for such a test in that the supply pressure is limited to a safe level for the cow. However, the test rig itself was not designed to be mobile, so setting it up would require some altering.

8.3 Controller

Model predictive control (MPC) is a well-established technology for advanced process control (APC) in many industrial applications. PID controllers are used as single-loop controllers, while MPC is used as an overall system. PID handles only single input and single output (SISO) systems, while MPC is a more advanced method of process control used for MIMO systems. The primary advantage of MPC is its ability to deal with constraints. PID controller does not have the ability to deal with the constraints.

Using model predictive control enables optimization. For example, there is less variation in process variables (PVs), which allows set points to be chosen that are closer to performance boundaries. This leads to increased throughput and a higher profit, which could be minimizing the cost generated due to state change of vacuum level. MPC brings a structured approach to solutions that would otherwise consist of combinations of feed-forward and feedback with PID controllers, possibly with override functions.

8.4 Reinforcement Learning

Reinforcement learning is a type of machine learning in which an agent learns to take action in an environment in order to maximize a reward. To design a reinforcement learning controller, it is required to define the environment in which the controller will operate, as well as the specific goals or objectives that the controller is trying to achieve. Since the exact model of pressure behaviors at milking systems is difficult to extract, it is considered to treat the model as a Markov Decision Process with the milk flow and milk system components. The actions are the valve behavior and the pressure at the cluster is the continuous state, thus, the controller would then use reinforcement learning algorithms to learn the optimal policy for taking actions in the environment in order to maximize the reward. The actions the controller can take, and the rewards or penalties it will receive for taking each action. This would involve exploring the environment, trying out different actions, and learning from the resulting rewards and penalties to improve the controller's performance over time.

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Appendix A

Design

A.1 Equations

$$\Delta P = \left(1 - \frac{\frac{Q_a}{A_t}\frac{P_{atm}}{(P_o+\frac{\Delta P}{2})}}{1.2(\frac{Q_m}{A_t} + \frac{Q_a}{A_t}\frac{P_{atm}}{(P_o+\frac{\Delta P}{2})}) + \upsilon_\infty}\right)\times$$
$$\left(\rho_m g H + \lambda \rho_m \frac{L_t}{D}\frac{(\frac{Q_m}{A_t} + \frac{Q_a}{A_t}\frac{P_{atm}}{(P_o+\frac{\Delta P}{2})})^2}{2} + \xi\rho_m\frac{L_t}{D}\frac{(\frac{Q_m}{A_t} + \frac{Q_a}{A_t}\frac{P_Patm}{(P_o+\frac{\Delta P}{2})})^2}{2}\right) \quad (A.1)$$

where velocity υ_∞ is calculated using the following formula:

$$\upsilon_\infty = k_1\sqrt{(\frac{g(\rho_m - \rho_a)D}{\rho_m})}$$

$$where: k_1 = 0.345\left(1 - e^{\frac{-0.01\sqrt{Ar}}{0.345}}\right)\cdot\left(1 - e^{\frac{3.37-E_o}{M_1}}\right)$$
$$= 0.345\left(1 - e^{\frac{-0.01\sqrt{\frac{g}{(\upsilon_m\rho_m)^2}(\rho_m - \frac{P}{RT})D^3}}{0.345}}\right)\cdot\left(1 - e^{\frac{3.37-\frac{g}{\sigma}(\rho_m-\frac{P}{RT})D^2}{M_1(Ar)}}\right) \quad (A.2)$$

- Q_m, Q_a - flow of milk [kg min^{-1}] and air [m^3 h^{-1}];
- D - diameter of milk tube [m];
- L_t - length of the milk tube [m];
- P_o - operating pressure [kPa];
- P_{atm} - atmospheric pressure in normal conditions [kPa];
- ρ_m, ρ_a - density of milk and air [kg min^{-1}];
- A_t - cross-sectional area of milk tube [m^2];
- υ_∞ - velocity of rising a single bubble in a still liquid [m s^{-1}];
- T - temperature [K];
- R - air gas constant [287 J kg K^{-1}];
- σ - surface tension of the liquid [N m^{-1}]

This model was based on these assumptions:

- Linear velocity is the sum of the velocity of the milk/air mixture with a coefficient characterizing a turbulent flow (1.2 u_M) and rise velocity of a single bubble ∞ in a quiescent liquid,
- the reduced air velocity requires the actual conditions to be lowered to normal conditions (a change in pressure causes a change in gas volume),
- the rise velocity of a single bubble in a quiescent liquid is the function of Archimedes (Ar) and Eötvös (Eo) numbers, which, due to the air density, depends on pressure in the long milk tube,
- volumetric air coefficient α in the milk tube is the quotient of the reduced velocity and linear velocity (calculated relative to the tube walls),
- for flows in the long milk tube, it can be assumed that $M_1 = M_1(Ar) = 10$
- when analyzing the value of derivative dv_∞/dp for g = $9.81\,\mathrm{m\,s^{-2}}$, D = 0.019 m, $\rho_m = 1030\,\mathrm{kg\,m^{-3}}$, T = 293.15 K, it was found that, for pressure variations ranging from 45,000 to 60,000 Pa, the derivative is approx. 0.6327 × 10−9 and is almost constant.
- The insensitivity of the rise velocity of a single bubble to pressure variations in the analyzed task results from the values of milk and air density. Milk density is $\rho_m = 1030\,\mathrm{kg\,m^{-3}}$, whereas air density at atmosphere pressure $P_{atm} = 101.3\,\mathrm{kPa}$ is $\rho_a = 1.225\,\mathrm{kg\,m^3}$. The ratio of these values is approx. 1000:1, so that the operating pressure P_o, bubble or air velocity υ_∞ can be treated as constant at certain milk flow.

Since υ_∞ is almost constant at certain milk flow, so substitutions $\upsilon_\infty = c$ and $\Delta P = x$ can be made. The equation can be rewritten as polynomials:

$$\pi^2 D^4(x^3 + 4P_o x^2 + 4P_o^2 x)\left[\frac{24Q_m}{5}(2P_o + x) + \frac{4.8 \times 10^6 Q_a}{5} + c\pi D^2(2P_o + x)\right] - \left[\frac{24Q_m}{5}(2P_o + x) + \frac{8 \times 10^5 Q_a}{5} + c\pi D^2(2P_o + x)\right] \times \left[\rho_m g H \pi^2 D^4 (2P_o + x)^2 + \frac{1}{10}(\lambda \rho_m \frac{L_t}{D})(24Q_m(2P_o + x) + 8 \times 10^5 Q_a)\right] = 0 \quad \text{(A.3)}$$

A.2 Milk divider

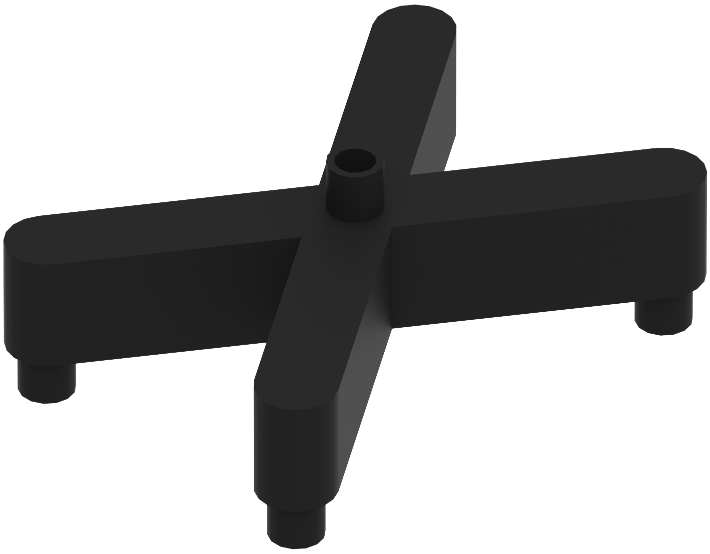


Figure A.1: The design of the milk divider, designed using Solid Edge

A.3 Pressure sensor

Metallux Product Catalogue Pressure Sensor ME780A00109000

ME78x/MEP78x datasheet

FLUSH DIAPHRAGM, PIEZORESISTIVE CERAMIC PRESSURE TRANSDUCER

Metallux ME78x and MEP78x pressure sensors are made with a ceramic base plate and a flush diaphragm and they work following the piezoresistive principle. The Wheatstone bridge is screen printed on one side of the flush ceramic diaphragm, which is in turn glued to the sensor's body. The bridge faces the inside where a cavity is made. Signal conditioning electronics is directly integrated on the ceramic to generate 0.5...4.5 V ratiometric output (ME780) or I^2C output with pressure and temperature information (ME782). Calibration performed electronically with the on-board ASIC and it can be performed in bar (ME78x) or in psi (MEP78x).
Electronics provides offset and span correction when the temperature changes. Zero correction software to compensate offset shift due to final customer assembly available on request. This allows good precision and long-term stability.
The Metallux ME78x family meets EMC requirements. The ASIC EEPROM stores production lot specific data for sensor traceability and it allows custom calibration.
Due to the excellent chemical resistance of the Al_2O_3 ceramic, the ME78x sensors are suitable for nearly all aggressive media.
Metallux ME78x are patented sensors.

FEATURES

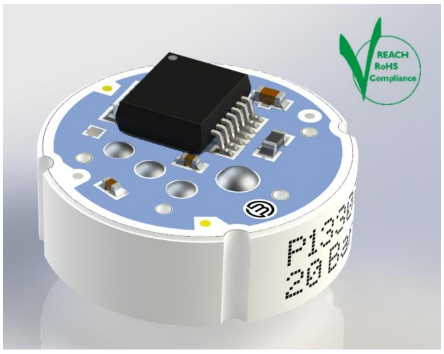
Excellent resistance to corrosion and abrasion

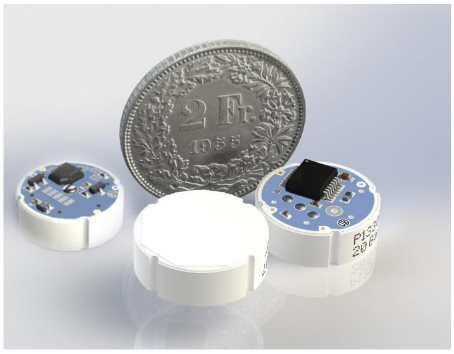
Fully integrated signal conditioning

EMC compliant

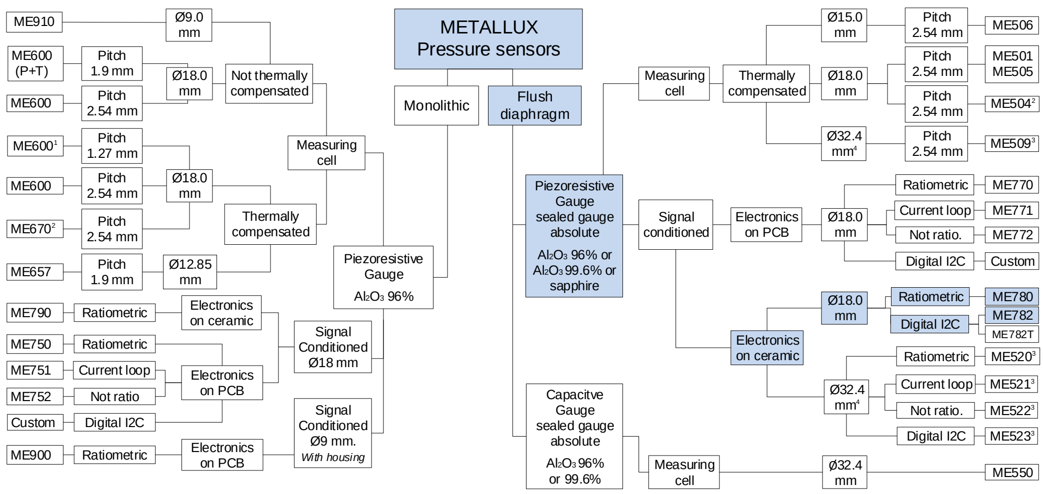
Thermally compensated

Zero stress mounting software





Pressure sensors family tree



[1] Also available in not thermally compensated version
[2] Digitally trimmed offset, also available not thermally compensated

[3] Not available with sapphire diaphragm.
[4] Suitable for low pressure range (≤1 bar)

Technical characteristics

Parameters	Units	ME780	ME782
Output	-	Ratiometric	Digital I^2C
Output range	-	0.5…4.5 [V]	Pres: 5…95% of 15bits (output register address: 0x78) Temp: 10…90% of 15bits (-40…125°C)
Sensor type	-	Flush diaphragm, absolute (A), gauge (R) or sealed gauge (S)	
Technology	-	Piezoresistive with electronic signal conditioning	
Diaph. material	-	Ceramic Al_2O_3 96%, 99.6% or sapphire	
Weight	g	≤ 9 (excluding connections)	
Response time	ms	≤ 5	
Supply voltage	VDC	4.5…5.5	3.3 or 5.0 (depending on calibration settings)
Max current[1]	mA	6 ($R_{LOAD} \geq 2$ kΩ)	4.5
Operating temp.	°C	-25…+125 (-13 °F…+257 °F)	-25…+105 (-13 °F…+221 °F)
Storage temp.	°C	-40…+135 (-40 °F…+275 °F)	-40…+125 (-40 °F…+257 °F)
Compliant with	-	Reach, RoHS, Conflict Minerals free	
EMC/ESD[2] compliances	-	Electrostatic discharge immunity: IEC/EN 61000-4-2(2009) Radiated electromagnetic field immunity: IEC/EN 61000-4-3(2006) Electrical fast transient (burst) immunity: IEC/EN 61000-4-4(2004) [2] Surge immunity: Not applicable Conducted RF immunity: IEC/EN 61000-4-6(2014)	

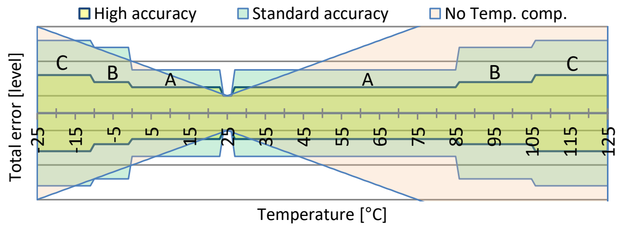
Pressure ranges			ME78x											
Nominal Pressure[3]	ME	bar	0.5	1	2	5	10	20	50	100	200	250	400	600
	MEP	*psi[4]*	*7.5*	*15*	*30*	*100*	*150*	*400*	1000	*1500*	*3000*	*4000*	*5000*	*8500*
Overload pressure		bar	1	2	4	10	15	35	100	150	350	350	500	750
		psi	*15*	*29*	*58*	*145*	*217*	*507*	1450	*2175*	*5075*	*5075*	*7250*	*10875*
Burst pressure		bar	2	3	6	15	25	65	120	200	500	500	650	950
		psi	*29*	*43*	*87*	*217*	*362*	*942*	1740	*2900*	*7250*	*7250*	*9425*	*13775*
Vacuum capability		bar	-0.1	-0.5	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
		psi	*-1.5*	*-7.3*	*-14.5*	*-14.5*	*-14.5*	*-14.5*	-14.5	*-14.5*	*-14.5*	*-14.5*	*-14.5*	*-14.5*
Pressure type		-	R	A/R/S	A/R/S	A/R/S	A/R/S	A/R/S	A/R/S	S	S	S	S	S
Sensor thickness		mm	6.15	6.17	6.23	6.30	6.35	6.55	6.70	6.70	7.05	7.05	7.32	7.55
		in	*0.242*	*0.243*	*0.245*	*0.248*	*0.250*	*0.258*	*0.263*	*0.263*	*0.278*	*0.278*	*0.288*	*0.297*

Accuracy [5] [%FS]	Calibration with high accuracy											
25°C (77 °F)	1.5		1.0								1.5	
A) 0…85 °C (32…185°F)	1.5				1.4		1.6	1.8	2.4			2.8
B)-10…105°C (14…221°F)	1.8				1.7		1.8	3.2	2.6			3.2
C)-25…125°C (-13…257°F)	2.2				2.0		2.2	3.5	3.1			3.5
Accuracy [5] [%FS]	**Calibration with standard accuracy**											
25°C (77 °F)	1.5		1.0								1.5	
A) 0…85 °C (32…185°F)	2.5				2.4		2.6	2.8	3.4			3.8
B)-10…105°C (14…221°F)	3.8				3.7		3.8	4.2	4.6			4.6
C)-25…125°C (-13…257°F)	4.2				4.0		4.2	4.5	5.5			5.5
Accuracy [5] [%FS]	**Calibration without thermal compensation**											
25°C (77 °F)	1.5		1.0								1.5	
-25…125°C (-13…257°F)	Max ± 0.08 %FS/K (Ceramic cell thermal offset shift + thermal span shift) + Accuracy at 25°C											

Unless indicated, all data are based on a reference temperature of 25°C and a power supply of 5 VDC.

1. During calibration or auto-zero, current consumption is < 30 mA.
2. All EMC/ESD test are performed inside grounded Metallux housing. EFT/Burst level is according to EN 61326-1:2013
3. Pressure ranges not listed in the technical chart have performances of the nearest listed pressure range. Contact us for customization.
4. Psi values are not the exact conversion of bar value. PSI ranges are defined to cover different standard values.
5. Accuracy includes room temperature error of non-linearity, hysteresis and non-repeatability, offset and span deviation PLUS thermal span shift and thermal offset shift. Accuracy calculation is performed in Metallux housings; accuracy excludes temperature hysteresis which primarily depends on mechanical conditions (housing, o-ring, etc) of actual application.

Total error band (full range) Only for error trend - Not in scale



Example of ME782 read out: .066E3529066E..

(Red = Pres. in hex – Green = Temp. in Hex – Black = Extra info)

$$P[bar] = \frac{P_{dec}}{32767} * \left(\frac{P_{max} - P_{min}}{B_p - A_p}\right) + \left[P_{min} - A_p\left(\frac{P_{max} - P_{min}}{B_p - A_p}\right)\right]$$

$$T\,[°C] = \frac{T_{dec}}{32767} * \left(\frac{T_{max} - T_{min}}{B_T - A_T}\right) + \left[T_{min} - A_T\left(\frac{T_{max} - T_{min}}{B_T - A_T}\right)\right]$$

P_{dec}= Decimal raw value of pressure (output of ASIC)

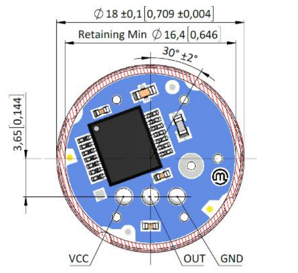
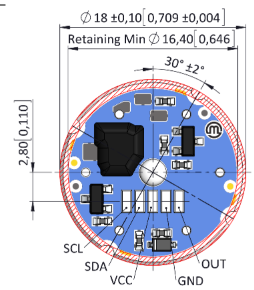
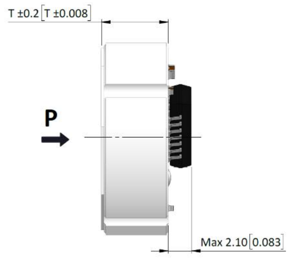
T_{dec}= Decimal raw value of temperature (output of ASIC)

P_{max}/P_{min}= Maximum/minimum pressure value in bar (depend by the pressure range of the sensor)

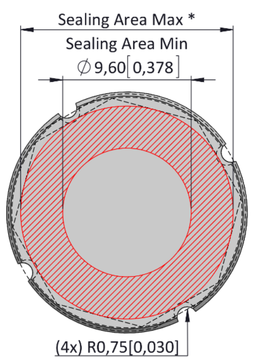
T_{max}/T_{min}= Maximum/minimum temperature value in °C (T_{max}=125°C and T_{min} = -40°C)

A_P = 0.05 B_P = 0.95 A_T = 0.10 B_T = 0.90

Mechanical drawings

ME780 Top View	ME782 Top View	ME78x Side View
		
ME780: 3x Pads ∅1.6 [0.063] Pitch = 2,54 [0,10]	ME782: 5x Pads 0,8 x 2,0 [0,031 x 0.0787] Pitch = 1,27 [0,05]	T = Sensor thickness (see page 2)

Bottom View (0.5...50 bar – 7.5...1000 psi)



*Sealing area max.	
Round	ø 15,7[0,618]
Octagonal	ø 14,7[0,579]

Diaphragm shape

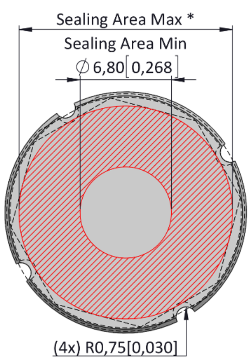
ROUND

ME	-	MEP
0.5 bar	-	7.5 psi
1 bar	-	15 psi
2 bar	-	30 psi

OCTAGONAL

ME	-	MEP
5 bar	-	100 psi
10 bar	-	150 psi
16 bar	-	300 psi
20 bar	-	400 psi
50 bar	-	1000 psi

Bottom View (100...600 bar – 1500...8500 psi)



*Sealing area max.	
Round	ø 15,7[0,618]
Octagonal	ø 14,7[0,579]

Diaphragm shape

OCTAGONAL

ME	-	MEP
100 bar	-	1500 psi
200 bar	-	3000 psi
250 bar	-	4000 psi
400 bar	-	5000 psi

ROUND

ME	-	MEP
600 bar	-	8500 psi

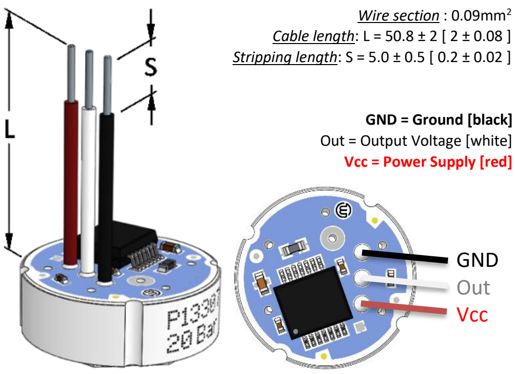
All quotes are in mm [inch] – General tolerance ISO 2768-1 M

Electrical terminations

ME780: type 0, wires L = 50.8 mm

Wire section : 0.09mm²
Cable length: L = 50.8 ± 2 [2 ± 0.08]
Stripping length: S = 5.0 ± 0.5 [0.2 ± 0.02]

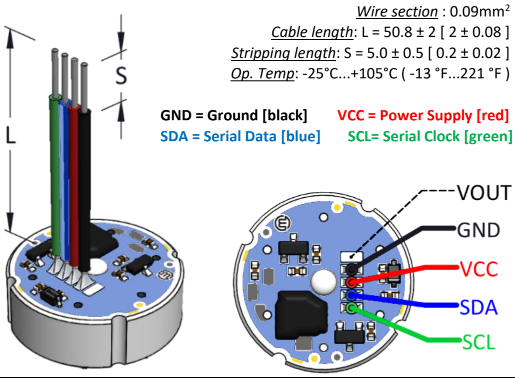
GND = Ground [black]
Out = Output Voltage [white]
Vcc = Power Supply [red]



ME782: type 0, wires L= 50.8 mm

Wire section : 0.09mm²
Cable length: L = 50.8 ± 2 [2 ± 0.08]
Stripping length: S = 5.0 ± 0.5 [0.2 ± 0.02]
Op. Temp: -25°C...+105°C (-13 °F...221 °F)

GND = Ground [black] **VCC = Power Supply [red]**
SDA = Serial Data [blue] **SCL= Serial Clock [green]**



All quotes are in mm [inch] – General tolerance ISO 2768-1 M

Ordering code

ME _ 78 _ _ _ _ _ _ _ _ _ _ _ _

Field	Option			Code
Pressure unit	bar			blank
	psi			P
Output signal	Ratiometric	0.5...4.5 [V]		0
	Digital I²C	5%...95% 15 bit ADC		2
Sensor Type	Absolute			A
	Gauge			R
	Sealed gauge			S
Pressure range	ME	MEP		ME – MEP
	0...0.5 bar or	0...7.5 psi	[-/R/]	0p5 – 7p5
	0...1bar or	0...15psi	[A/R/S]	001 – 015
	0...2 bar or	0...30 psi	[A/R/S]	002 – 030
	0...5 bar or	0...100 psi	[A/R/S]	005 – 100
	0...10 bar or	0...150 psi	[A/R/S]	010 – 150
	0...20 bar or	0...400 psi	[A/R/S]	020 – 400
	0...50 bar or	0...1000 psi	[A/R/S]	050 – 1k0
	0...100 bar or	0...1500 psi	[-/-/S]	100 – 1k5
	0...200 bar or	0...3000 psi	[-/-/S]	200 – 3k0
	0...250 bar or	0...4000 psi	[-/-/S]	250 – 4k0
	0...400 bar or	0...5000 psi	[-/-/S]	400 – 5k0
	0...600 bar or	0...8500 psi	[-/-/S]	600 – 8k5
	Others on request (enquiry for customization)			999 – 999
Calibration	High accuracy			0
	Standard accuracy			1
	No temperature compensation* (calibration done at room temperature)			2
	Not calibrated, not compensated (electrical test only)			3
	Others on request (enquiry for customization)			9
Termination type	Wires 50.8 mm			0
	Tinned pads			1
	Others on request (enquiry for customization)			9
Power Supply	5 V			0
	3.3 V (Only ME782)			1
Diaphragm type	Ceramic Al_2O_3 96.0% purity			0
	Different purity on request (Al_2O_3 99.6%, sapphire...)			9
Venting hole pipe	Without			0
	Venting pipe on request (Metal pipe Ø1.2 mm, for gauge sensor only)			9
Coating	Standard conformal coating			Blank
	Parylene or other coating (enquiry for customization)			Custom

* *ME782 temperature output is not available with this calibration option. Temperature signal is available only with high/standard accuracy.*

Conversion tools

Celsius	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Fahrenheit	-40	-20	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300		

bar	0	5	10	15	20	50	100	150	200	250	300	350	400
psi	0	72.5	145	217.5	290	725	1450	2175	2900	3625	4350	5075	5800

To be disposed of according to local regulations (OTRif 16 02 97 for Switzerland, CER 16 02 16 for European Union)

A.4 Milkmeter

(a) DeLaval milk flow indicator HFC designed for heavy-duty milking

(b) DeLaval flow sensor FI2 design to view in the background

(c) DeLaval yield indicator FI7 designed for data synchronization for efficient herd management

(d) DeLaval milk meter MM27BC designed for accurate ICAR approved milk meter

Figure A.2: Milkmeter on the market from DeLaval

A.5 AD Converter and DA converter

Listing A.1: Read from the sensor by Arduino with the help of MATLAB

```
clear
clc
close all
% connection = '/dev/cu.usbmodem143101';
connection = 'COM6';
board = 'uno';
pin0 = 'A0'; % Sensor inside the pinch
pin1 = 'A1'; % Sensor before the pinch valve
pin2 = 'A2'; % Sensor at the cluster
pin3 = 'A3'; % Flow meter
pin4 = 'A4'; % Potentialmeter

plotornot = true;

plotTitle = 'Arduino Pressure Data Log';  % plot title
xLabel = 'Elapsed Time (s)';      % x-axis label
yLabel = 'Pressure (hPa)';        % y-axis label
yLabel2 = 'Flow rate (L/min)';
legend1 = 'Pinch';
legend2 = 'Controller sensor';
legend3 = 'Cluster';
legend4 = 'Flow meter';
legend5 = 'Manual ref';
xMax = 40;
xMin = 0;
yMax  = 1200;                       % y Maximum Value
yMin  = 0;                          % y minimum Value
plotGrid = 'on';                    % 'off' to turn off grid
delay = 0.001;                      % make sure sample faster than
    resolution

%% connect arduino
a = arduino(connection,board);    % define the Arduino
   Communication port
configurePin(a,pin4,'AnalogInput');

%% Define Function Variables
time = 0;
data0 = 0; %zeros(1, 1000000);
data1 = 0; %zeros(1, 1000000);
data2 = 0; %zeros(1, 1000000);
data3 = 0;
data4 = 0;
count = 0;
count_LP = 1;
V_cluster = 0;
```

```
V_end = 0;
p0 = 0;
p1 = 0;
p2 = 0;
hp0 = 0;
hp1 = 0;
hp2 = 0;

atm = 100300;
k0 = -100000.0/4;
k1 = -100000.0/4;
k2 = 100000.0/5.5;
m0 = 100000.0-(k0*0.895);
m1 = 100000.0-(k1*0.895);
m2 = 100000.0-(k2*4.425);
% [bf,af]=butter(1,1/(5/2));

%% Set up Plot
figure('units','normalized','outerposition',[0 0 1 1])
hold on  %hold on makes sure all of the channels are plotted
plotGraph = plot(time,data0,'-r' );  % every AnalogRead needs to be on its own Plotgraph
plotGraph1 = plot(time,data1,'-b');
plotGraph2 = plot(time,data2,'-g' );
plotGraph3 = plot(time,data3,'--m');
plotGraph4 = plot(time,data4,'-k');
title(plotTitle,'FontSize',15);
xlabel(xLabel,'FontSize',15);
ylabel(yLabel,'FontSize',15);
yyaxis right
ylabel(yLabel2,'FontSize',15);
ylim([0 20]);
yyaxis left
legend(legend1,legend2,legend3,legend4,legend5,"Location","bestoutside")
axis([xMin xMax yMin yMax]);
grid(plotGrid);
% set(gcf,"Position",[0 0 1920 1080])
%% Arduino loop
axis_timer = tic;
while ishandle(plotGraph) % Loop when Plot is Active will run until plot is closed
    test_timer = tic;
    V_cluster = readVoltage(a,pin0);
    V_end = readVoltage(a,pin1);
    V_pinch = readVoltage(a,pin2);
    V_F = readVoltage(a,pin3);
```

```
    V_ref = readVoltage(a,pin4);

    p0 = k0*V_cluster+m0;
    p1 = k2*V_end+m2;
    p2 = k1*V_pinch+m1;
    hp0 = p0/100.0;
    hp1 = p1/100.0;
    hp2 = p2/100.0;
    flowmeter = V_F/5*60*60;
    ref = V_ref*(200/5) + 450; %V_ref * 230/5+370
    count = count + 1;

    time(count) = toc(axis_timer);
    data0(count) = hp0; % pinch
    data1(count) = hp1; % end
    data2(count) = hp2; % cluster
    data3(count) = flowmeter;
    data4(count) = ref;
    data2f(count) = kalmans(data2(count));
%     data0f(count) = kalmans(data0(count));
%     data1f(count) = kalmans(data1(count));
%     data3f(count) = kalmans(data3(count));
%     data4f(count) = kalmans(data4(count));
    %Transmit to other arduino
    %Serial.write(hp0);

    try
        set(plotGraph,'XData',time,'YData',data0);
        set(plotGraph1,'XData',time,'YData',data1);
        set(plotGraph2,'XData',time,'YData',data2f);
        set(plotGraph3,'XData',time,'YData',data3);
        set(plotGraph4,'XData',time,'YData',data4);
    catch
        fprintf('failed last datapoint\n');
        continue
    end

    axis('auto');
    ylim([yMin yMax])

    %fprintf('d-toc: %f\n',delay-toc(test_timer))
    pause(delay-toc(test_timer));
end

% Added data4 (reference) to the variables being saved

save_vars = [time;data0;data1;data2;data3/60;data4].';
```

```
writematrix(save_vars,'test.csv');
save('test.mat','time','data0','data1','data2','data3', 'data4'
    );
clear a
disp('Plot Closed and arduino object has been deleted');
%% plot
if plotornot == true
    load('test.csv')
    hold on
    test_rolled = rolling_avg(test,700);
%     plot(test(:,1),test(:,2),'LineWidth',0.6)
    plot(test_rolled(:,1),atm/100-test_rolled(:,2),'LineWidth'
        ,1)
    plot(test_rolled(:,1),atm/100-test_rolled(:,3),'LineWidth'
        ,1)
    plot(test_rolled(:,1),atm/100-test_rolled(:,4),'LineWidth'
        ,1)
    plot(test_rolled(:,1),atm/100-test_rolled(:,6), 'LineWidth'
        , 1.5) % Reference
    title('Arduino Vacuum Data Log','FontSize',15);
    xlabel(xLabel,'FontSize',20);
    ylabel('Vacuum (hpa)','FontSize',20);
    %yline(450); % Dödar denna
%     legend(legend1,legend2,legend3)
    ylim([-10 700]);
    yyaxis right
    plot(test(:,1),test(:,5),'LineWidth',1)
    ylabel(yLabel2,'FontSize',15);
    legend(legend1,legend2,legend3,"Reference","Flow");
    axis('auto');
    ylim([0 20]);
    grid(plotGrid);
    exportgraphics(gcf,"test.pdf","ContentType","vector")
else
    disp('Fxxk off! Try another test!');
end
```

A.6 Controller

```
/*
 * FileName: Outer_Loop_2_Kalman.ino
 * FileType: Arduino .ino file
 * Authors: C.Egenas, F.Ekman, C.Ma, T.Naser, X.Niu, A.Sernelin, S. Stenow,
    B. Strom
 * Description: KTH HK DeLaval 2022 cascade control for regulating pressure
    at milking cluster
 */

```

```
/*
 Designations:
   End sensor - The sensor just before the pinch valve
   Pinch sensor - The sensor inside the pinch valve chamber
   Cluster sensor - The sensor at the cluster
*/

// Pre-compiler Variables (Pin declarations)
#define sensorPin1 A0  // Pinch Sensor
#define sensorPin3 A1  // End Sensor
#define sensorPin2 A2  // Cluster Sensor
#define sensorPin5 A3  // Flow meter
#define sensorPin4 A4  // Potentiometer

#define valveVac 11 //PWM actuation pin

// SENSOR CALIBRATION VARIABLES
static const double k0 = -100000.0/818.4;  // Slope of pinch sensor 2 point calibration
static const double k1 = -100000.0/818.4;  // Slope of end sensor 2 point calibration
static const double k2 = 100000.0/1125.3;  // Slope of the cluster sensor 2 point calibration
static const double m0 = 100000.0-(k0*183.117);  // y-intersection of the pinch sensor 2 point calibration
static const double m1 = 100000.0-(k1*183.117);  // y-intersection of the end sensor 2 point calibration
static const double m2 = 100000.0-(k2*905.355);  // y-intersection of the cluster sensor 2 point calibration

// End-Cluster mapping
static const double k_ec = 5.2;  // Slope of linear end-cluster relationship
static const double m_ec = 5;  // y-intersection of linear end-cluster relationship

// PID parameters
static const double Kp1 = 0.25;
static const double Ki1 = 0.00000000001;
static const double Kd1 = 10;
static const double Kp2 = 0.15;
static const double Ki2 = 0.00000000002;
static const double Kd2 = 1;

// pwm actuation variable
double pwm = 100.0;

// SETUP
void setup() {
  Serial.begin(9600);
  pinMode(sensorPin1, INPUT);
  pinMode(sensorPin2, INPUT);
  pinMode(sensorPin3, INPUT);
  pinMode(sensorPin4, INPUT);
  pinMode(sensorPin5, INPUT);
  pinMode(valveVac, OUTPUT);
}
```

```

// MAIN LOOP
void loop() {

  double hp2 = readnplot2();  // read current pressure at cluster sensor (for viewing only)

  // Get reference from outer loop
  double r2 = read_ref();  // read manual reference potentiometer for outer loop reference (cluster pressure reference)
  double flow = read_flow();  // get flow value for end-cluster estimation
  double hp3 = readnplot4(flow);  // read current pressure at "End" sensor AND estimate cluster pressure
  double r1 = PIDMAN_outer(hp3, r2);  // outer loop actuation (returns reference to inner loop)
  Serial.print("u_inner:");
  Serial.print(r1);
  Serial.print(" ");

  // Actuate inner loop
  double hp1 = readnplot1();  // read current pressure in pinch valve
  pwm = PIDMAN_inner(hp1, r1);  // Get pwm to actuate pwm valve with r1
  actuatePwmValve(pwm); // actuate pwn valve
  Serial.println(" ");

}

// Inner Loop
double PIDMAN_inner(double output, double reference){
  // Variable declarations
  static double pwm;
  static double e_inner = 0.0, etot_inner = 0.0, prevError_inner = 0.0, delta_error_inner= 0.0;
  static double P_inner = 0.0, I_inner = 0.0, D_inner = 0.0;
  static unsigned long currTime_inner;
  static unsigned long prevTime_inner = 0.0;
  static int deltaTime_inner = 0;

  // Time vars
  currTime_inner = millis();
  deltaTime_inner = currTime_inner - prevTime_inner;
  prevTime_inner = currTime_inner;

  // Error terms
  e_inner = reference - output;
  etot_inner += e_inner;
  delta_error_inner = e_inner - prevError_inner;
  prevError_inner = e_inner;

  // Control parts
  P_inner = Kp1*e_inner;
  I_inner = (Ki1*deltaTime_inner)*etot_inner;
  D_inner = (Kd1/deltaTime_inner)*delta_error_inner;

  // PWM signal output
  pwm = pwm - (P_inner + I_inner + D_inner);

```

```
  // Anti-windup
  if(pwm > 255.0){
    pwm = 255.0;
    etot_inner = 0;
  }
  else if(pwm < 0.0){
    pwm = 0.0;
    etot_inner = 0;
  }

  return pwm;
}

// Outer Loop
double PIDMAN_outer(double output, double reference){
  // Variable declarations
  static double u = 500.0;
  static double e = 0.0, etot = 0.0, prevError = 0.0, delta_error = 0.0;
  static double P=0.0, I=0.0, D=0.0;
  static unsigned long currTime;
  static unsigned long prevTime = 0.0;
  static int deltaTime = 0;

  //Time stuffs
  currTime = millis();
  deltaTime = currTime - prevTime;
  prevTime = currTime;

  // Error terms
  e = reference - output;
  etot += e;
  delta_error = e - prevError;
  prevError = e;

  // Control parts
  P = Kp2*e;
  I = (Ki2*deltaTime)*etot;
  D = (Kd2/deltaTime)*delta_error;

  // outer PID output (pressure reference for pinch valve)
  u = u + (P + I + D);


  // Anti-windup
  if(u > 1000.0){
    u = 1000.0;
    etot = 0;
  }
  else if(u < 300.0){
    u = 300.0;
    etot = 0;
  }

  // Return reference signal for inner loop
  return u;
}

```

```
// Read pinch valve sensor function
double readnplot1(){
  static double adc1 = 0.0;  // ADC read variable
  static double p_pinch = 0.0;  // pinch pressure
  static double hp1 = 0.0;  // hPa
  adc1 = analogRead(sensorPin1);
  p_pinch = k0*adc1+m0;
  hp1 = p_pinch/100.0;
  Serial.print("Pinch:");
  Serial.print(hp1);
  Serial.print(" ");
  return hp1;
}

// Read cluster sensor function
double readnplot2(){
  static double adc2 = 0.0;  // ADC read variable
  static double p_cluster = 0.0;  // Cluster pressure
  static double hp2 = 0.0, hp2_kalman=0.0;  // hPa
  adc2 = analogRead(sensorPin2);
  p_cluster = k1*adc2+m1;
  hp2 = p_cluster/100.0;
  Serial.print("Cluster:");
  Serial.print(hp2);
  Serial.print(" ");
  return hp2;
}

// Read end sensor function
double readnplot4(double flow){
  static double adc3 = 0.0;  // ADC read variable
  static double p_end = 0.0;  // End sensor pressure
  static double hp3_raw = 0.0, hp2_est = 0.0, hp3_filtered=0.0; //hPa
  adc3 = analogRead(sensorPin3);  // read end sensor value
  p_end = k2*adc3+m2;
  hp3_raw = p_end/100.0;
  hp3_filtered = KALMAN(hp3_raw);  // Filter the signal
  hp2_est = 5.15*flow + 5.0+ hp3_filtered;  // Estimation of cluster
    pressure
  Serial.print("Cluster_est:");
  Serial.print(hp2_est);
  Serial.print(" ");

  Serial.print("End:");
  Serial.print(hp3_raw);
  Serial.print(" ");
  return hp2_est;
}

// Read potentiometer function (manual reference)
double read_ref() {
  int sensorValue = analogRead(sensorPin4);
  double scale = 200/1023.0;
  double ref_pin = sensorValue * scale + 450.0; //Limits reference to
    operation range
  Serial.print("ref:");
  Serial.print(ref_pin);
```

```
  Serial.print(" ");
  return ref_pin;
}

// Kalman filter
double KALMAN(double u) {
  // Kalman filter variables
  static const double R = 10^2; // noise covariance
  static const double H = 1.00; // measurement map scalar
  static double Q = 0.1; // initial estimated covariance
  static double P = 0.0; // initial error covariance (must be 0)
  static double u_hat = 550.0; // initial estimated state (assume we don't
    know)
  static double K = 0.0; // initial Kalman gain

  // Begin
  K = P*H/(H*P*H+R); // update kalman gain
  u_hat = u_hat + K*(u-H*u_hat); // update estimated

  // Updated error covariance
  P = (1-K*H)*P + Q;

  // Return the estimated of U-H*U_hat
  return u_hat;
}

double read_flow() {
  int sensorValue = analogRead(sensorPin5);
  double scale = 1.0/1023.0 * 60;
  double flow = sensorValue * scale;
  Serial.print("flow:");
  Serial.print(flow);
  Serial.print(" ");
  return flow;
}

void actuatePwmValve(double pwm){
  analogWrite(valveVac,pwm);
}
```

Listing A.2: PID controller code for Arduino

Appendix B

Project organization

B.1 Risk analysis

Risk Assessment					
Risk Categories	Risk Description	Risk Probability	Risk Severity	Risk Score	Strategy
Technical	Key component breaking	Low	Medium	30	Have extras of the cheaper components ready in case. Any more expensive key component will be provided by DeLaval and replacements should be manageable
	Control system not satisfying stake-holders	High	Low	8	The control system does not neccecarily have to work as long as a reason or conclusion can be made
	Test rig not working	Medium	High	60	The main focus should be on the test rig working. Starting and progressing as early as possible on the test rig will allow room for errors and tuning
External	Delayed delivery of key component	Low	Medium	15	A key component missing can result in critial to catastophic consequences. Ordering as soon as possible is the best way to minimize the risk
	Stakeholders change the requirements	Low	Low	3	Consistent and frequent meetings will avoid this risk.
Organizational	Workshop or construction access delayed	Low	High	30	Contact with the coach and meetings with the examinators will minimize this risk
	Components not feasible due to price	Low	Low	3	Prestudies lowers the risk. Even if components can't be used in the end product, the data can be valuable
Project Management	Different understand-ing of what needs to be done within the group	Medium	Medium	30	Clear communication and frequent meetings lowers the probability. Misunderstandings can be cleared if they are spotted early enough.
	The group falling behind schedule	High	Low	8	Falling behind does not mean that the delivery due date will be neglected. More work hours will compensate for delays.
	Late on final delivery	Low	High	30	Everything done previously is to avoid this outcome.

Figure B.1: Impact-Probability Matrix

B.2 List of material

Material (Final prototype)	Quantity	Total cost (SEK)	Colour definitions
Aim Tti EX354RT triple power supply	1	6500	Own design
Aluminium profiles	9m	3510	Provided by DeLaval
Angle bracket	8	800	Provided by KTH
Arduino Uno	2	540	
Bolts M8	40	200	
Brackets	12	120	
Cluster (DeLaval)	1		
Electrical box + shelves (3D-print, PLA)	1	150	
Fake cow teets (DeLaval)	4		
Flowmeter + belonging power supply (DeLaval)	1		
GAST Rotary vane vacuum pump (3032-701-RM112)	1	700	
Hard plastic plug (Ø75mm, DeLaval)	2		
Hard plastic tube (Ø55mm, DeLaval)	1.5m		
Hard plastic tube (Ø75mm, DeLaval)	0.8m		
Hose clamps	17	360	
Hose couplers (3D-print,PLA)	3	20	
Hose couplers (metal)	5	100	
Inverted pich valve (3D-print, PLA + plexiglas)	1	30	
Lubricant oil (vacuum pump)	1	500	
Milkmeter (DeLaval)	1		
Nut M8	38	150	
PCB + transistor + molex + diode + resistor	2	200	
Plastic tube connector, two way (Ø55mm, DeLaval)	1		
Plywood	0.017 m3	300	
Pressure gauge (DeLaval)	1		
Pressure sensor (DeLaval)	3		
Pressure sensor housing (PLA, 3D-printed)	3	20	
Pressure sensor ME78x (DeLaval)	3		
Proportional valve (DeLaval)	1		
Rubber tube (Ø16mm, DeLaval)	6.4m		
Rubber tube (Ø19mm, DeLaval)	7.7m		
Rubber tube (Ø7mm, DeLaval)	1.7m		
Teatcup mounts (PLA, 3D-printed)	4	50	
Universal converter bipolar Z109REG	1	2000	
Vacuum pulsator (DeLaval	1		
Vacuum tank (DeLaval)	1		
Vevor 10CFM 1HP vacuum Pump 254 L/m	1	2216	
Wall panel (tool holder) 1950x900 mm	1	1830	
Water divider (3D-print, PLA)	1	15	
Water Tank (DeLaval)	1		
Wires	many	100	
Zip tie	36	50	
Total Price:		20411	

Figure B.2: List of material

B.3 Kanban and Timeline

Constructed Kanban and Timeline from Notion, click here.

Figure B.3: QR code to the timeline site

Appendix C

Drawings

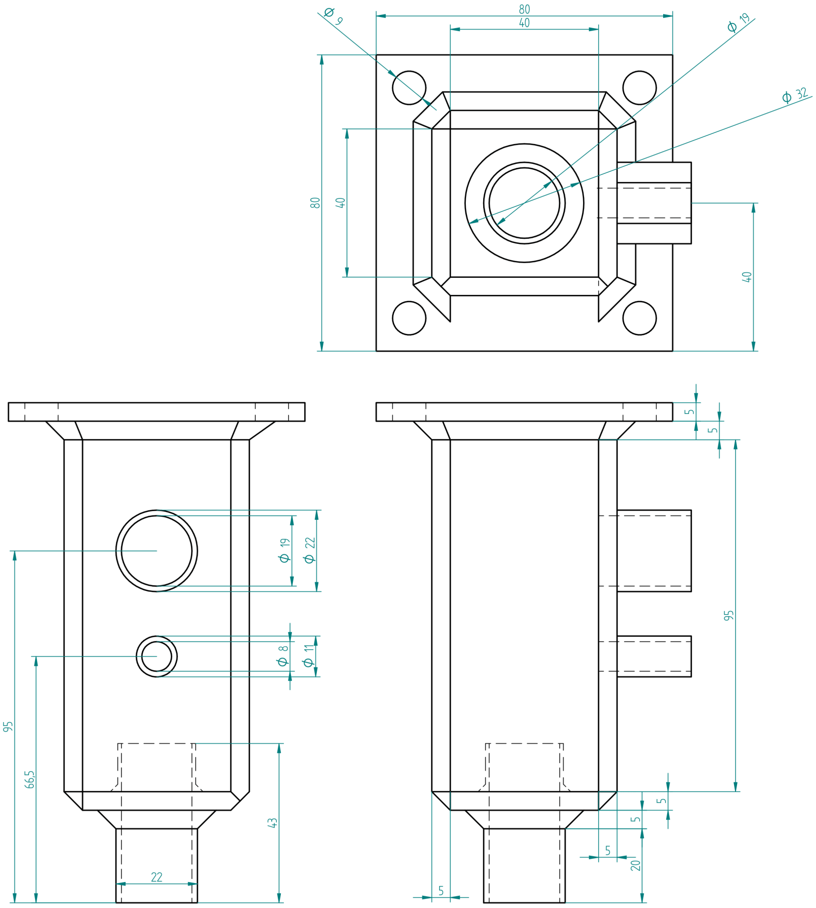


Figure C.1: Drawing of pinch valve chamber.

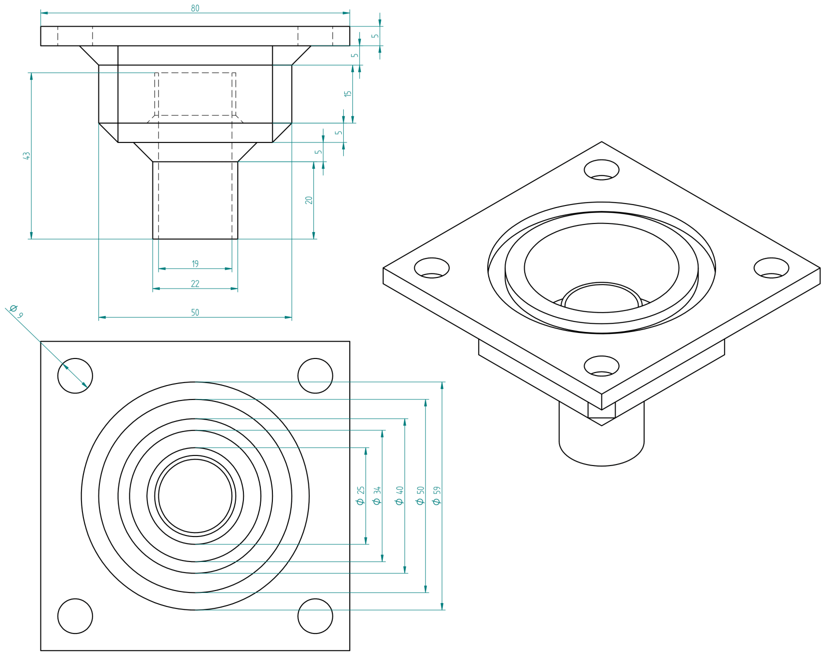


Figure C.2: Drawing of pinch valve chamber.

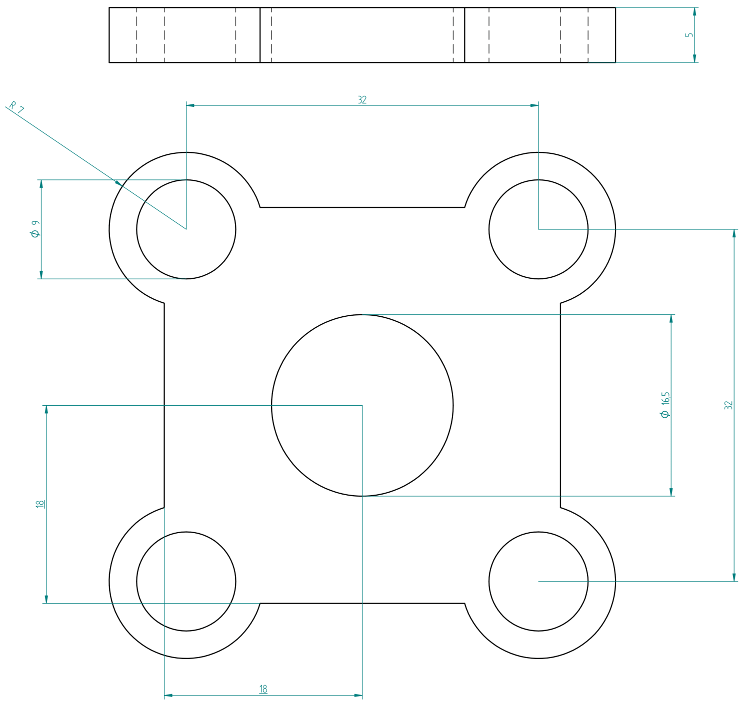


Figure C.3: Drawing of Sensor housing lid.

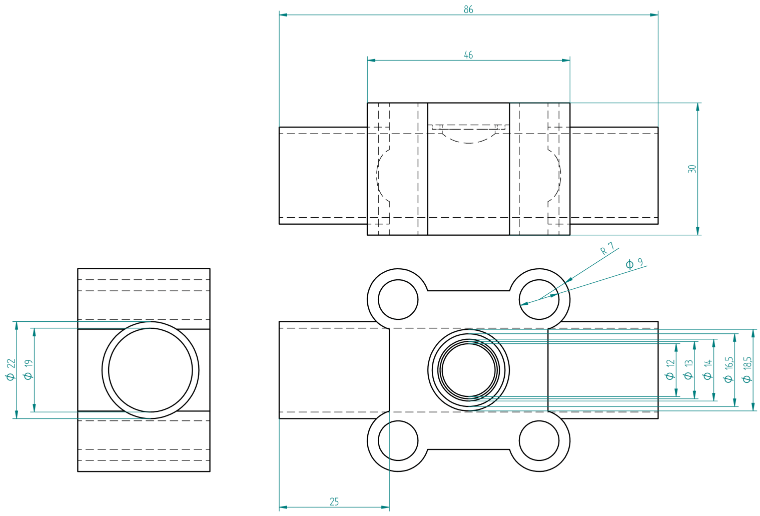


Figure C.4: Drawing of sensor housing.

Appendix D

Test Rig Site

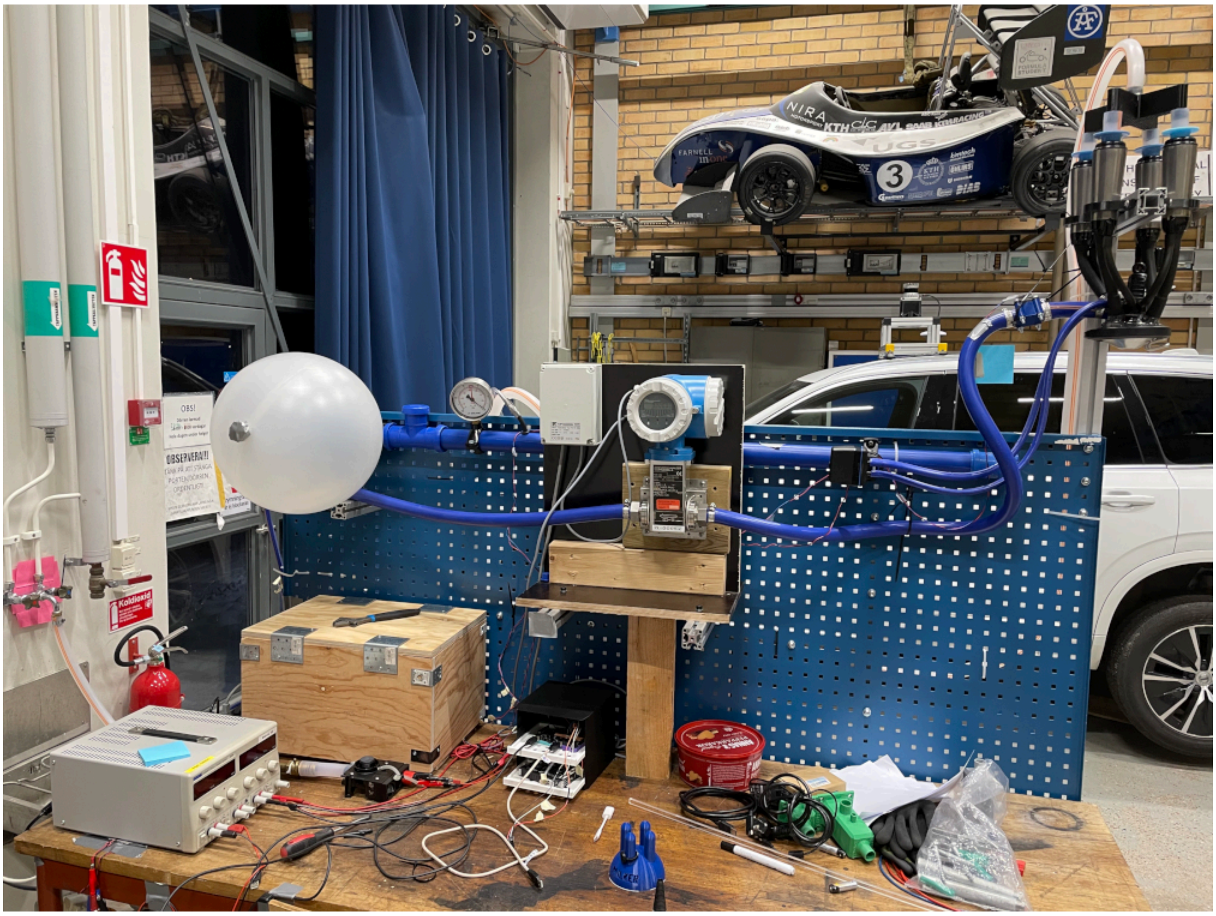


Figure D.1: Front side of the test rig

Figure D.2: Back side of the test rig

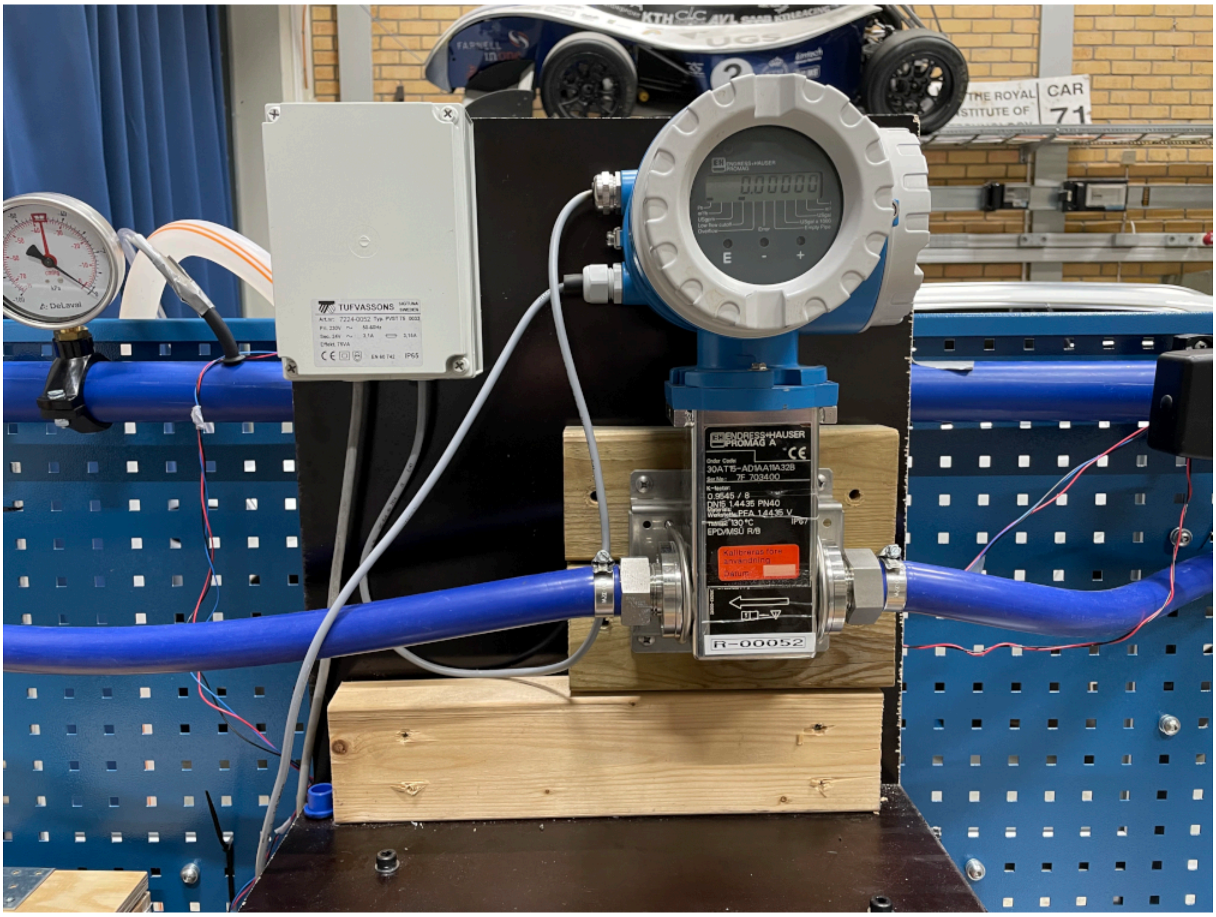


Figure D.3: Closeup of the flow sensor.

Figure D.4: Cluster and water divider.

Figure D.5: Closeup of cluster and water divider.

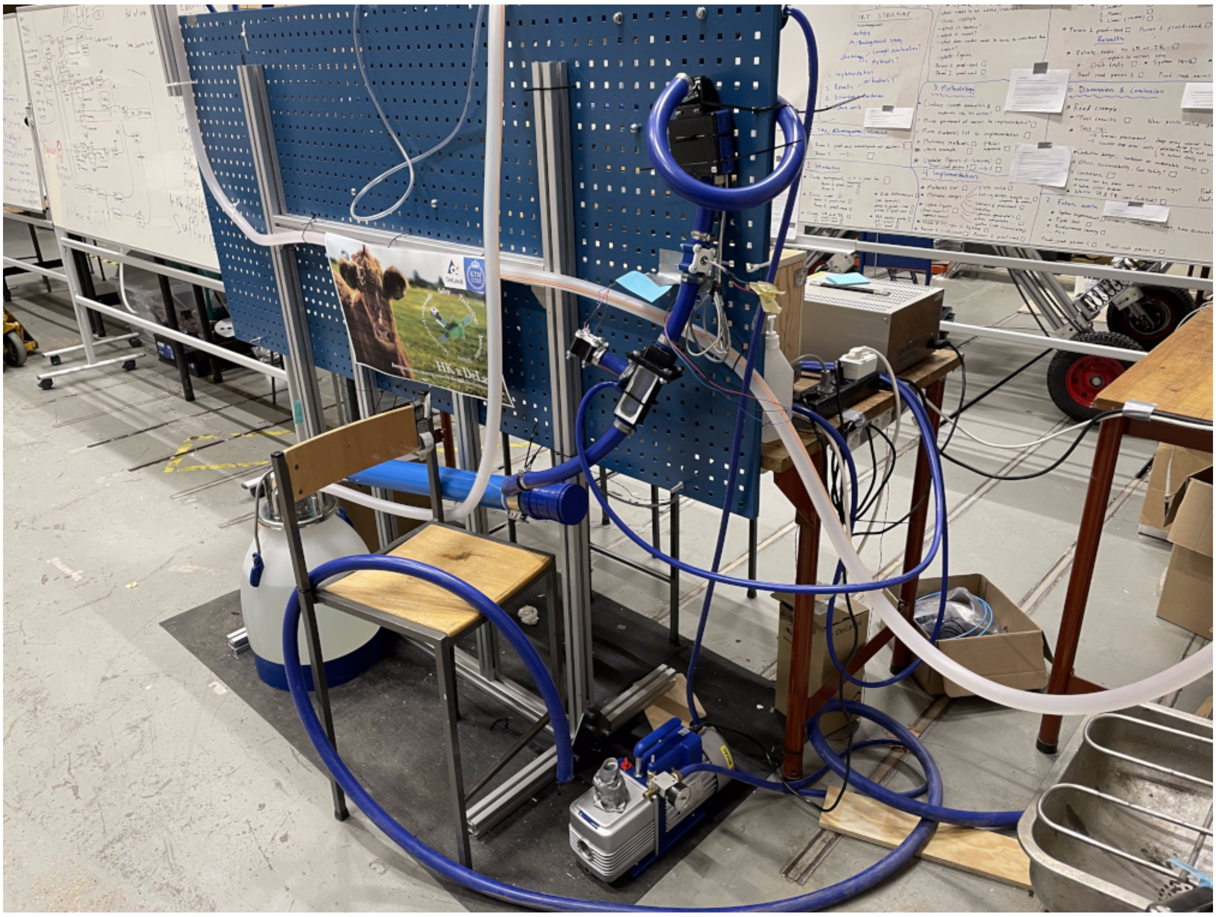


Figure D.6: Backside of the test rig showing the inverted pinch valve, the milk-meter and the vacuum pump.

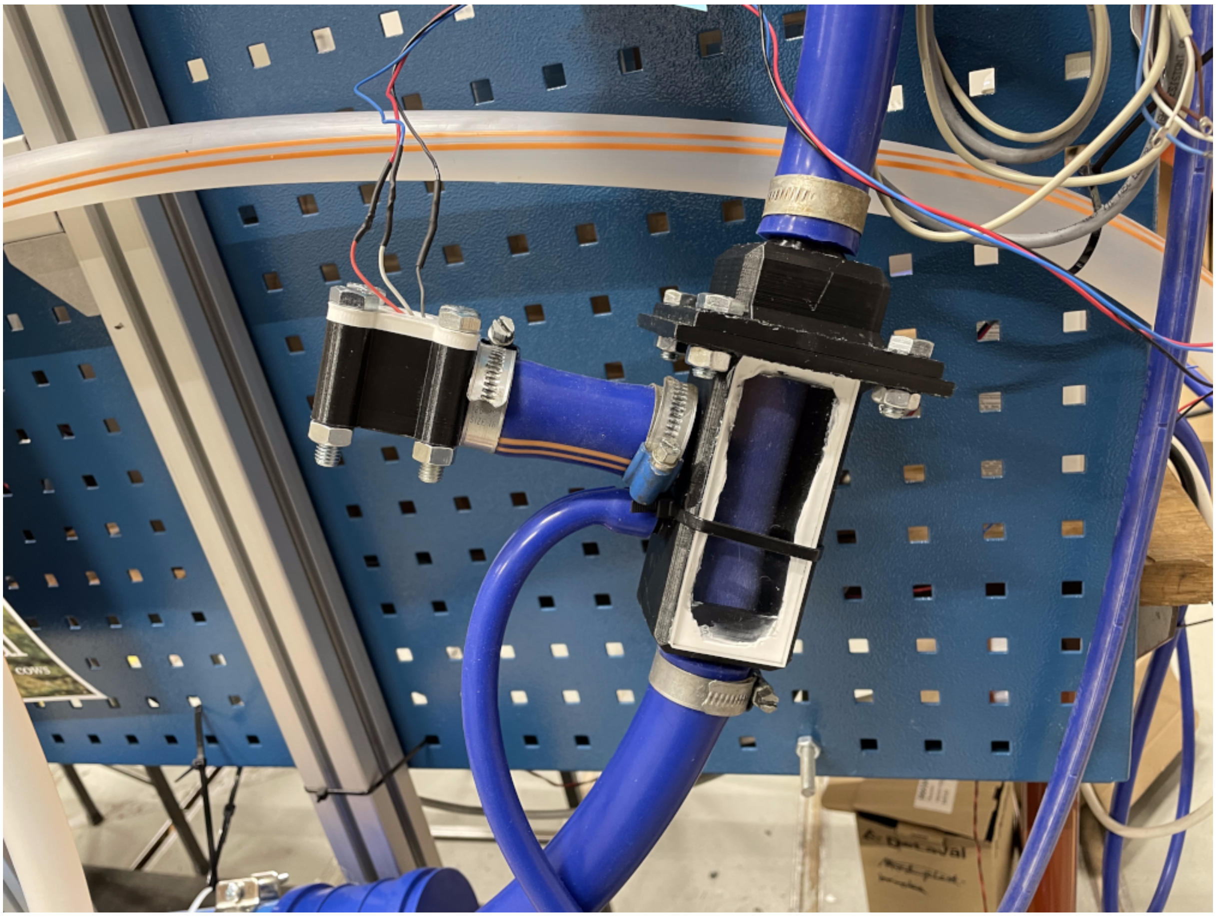


Figure D.7: Close up of the inverted pinch valve.

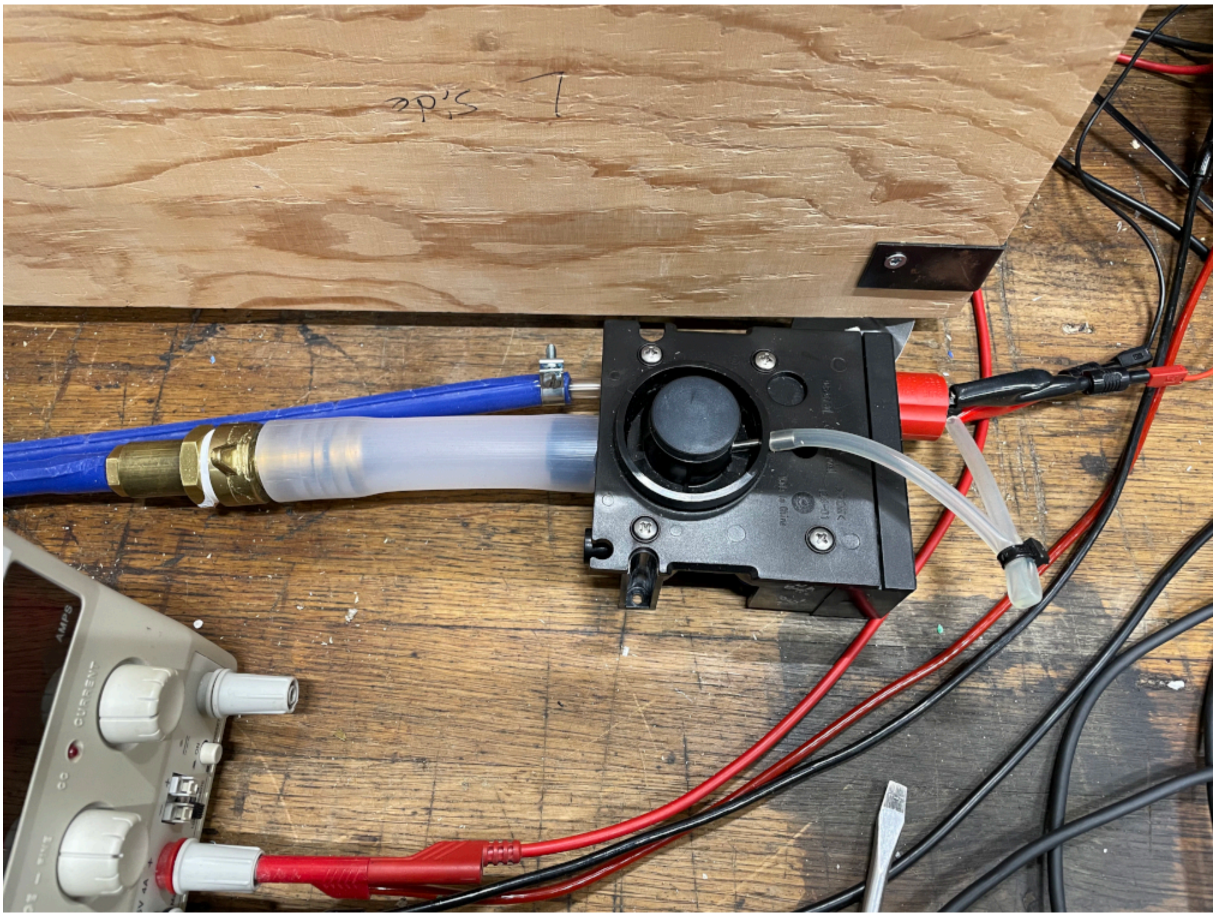


Figure D.8: Proportional valve used to regulate the inverted pinch valve chamber vacuum.

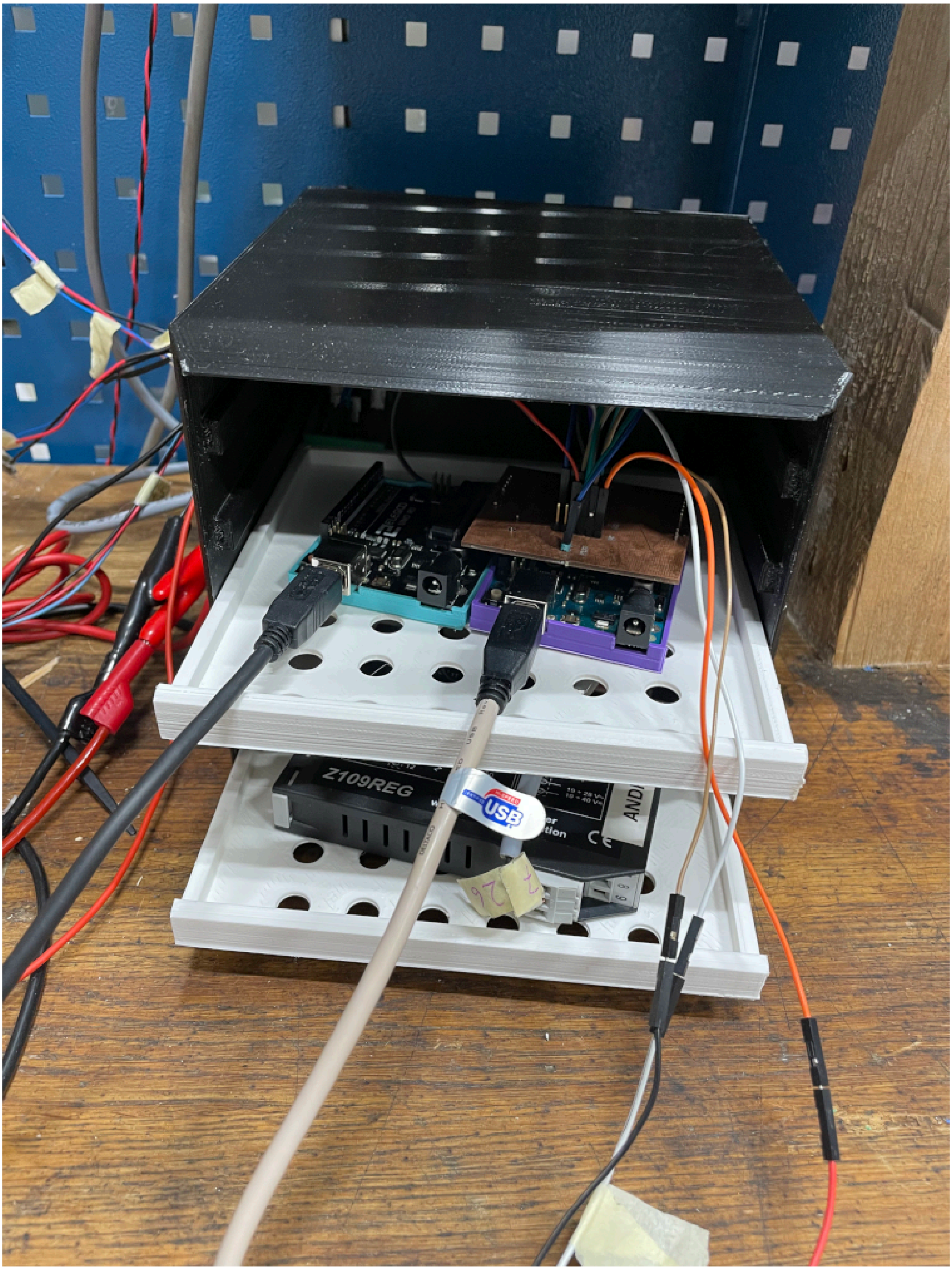


Figure D.9: Most of the electronics housed in a 3D-printed box.

Appendix E

Electrical circuit

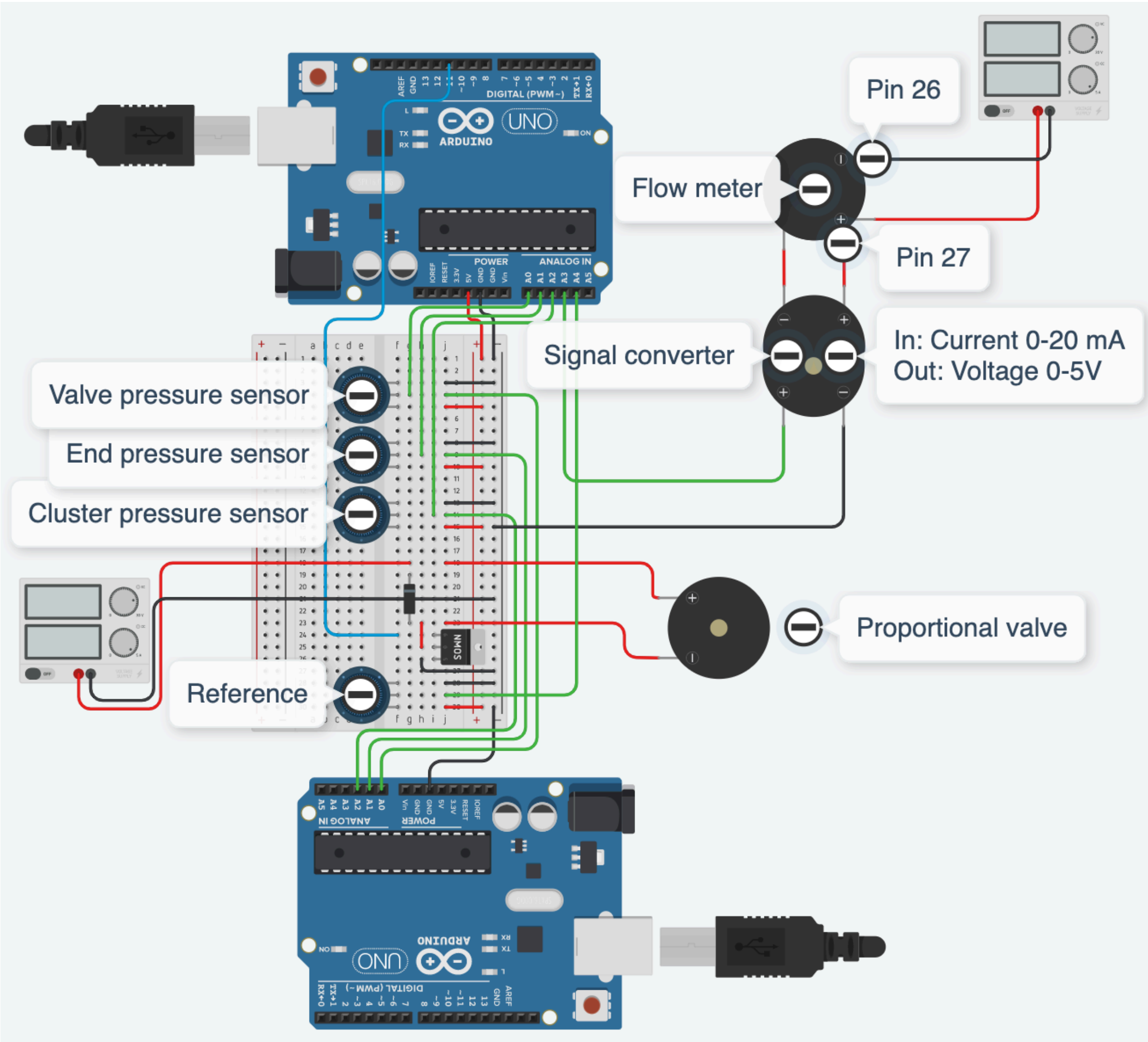


Figure E.1: Electrical circuit.