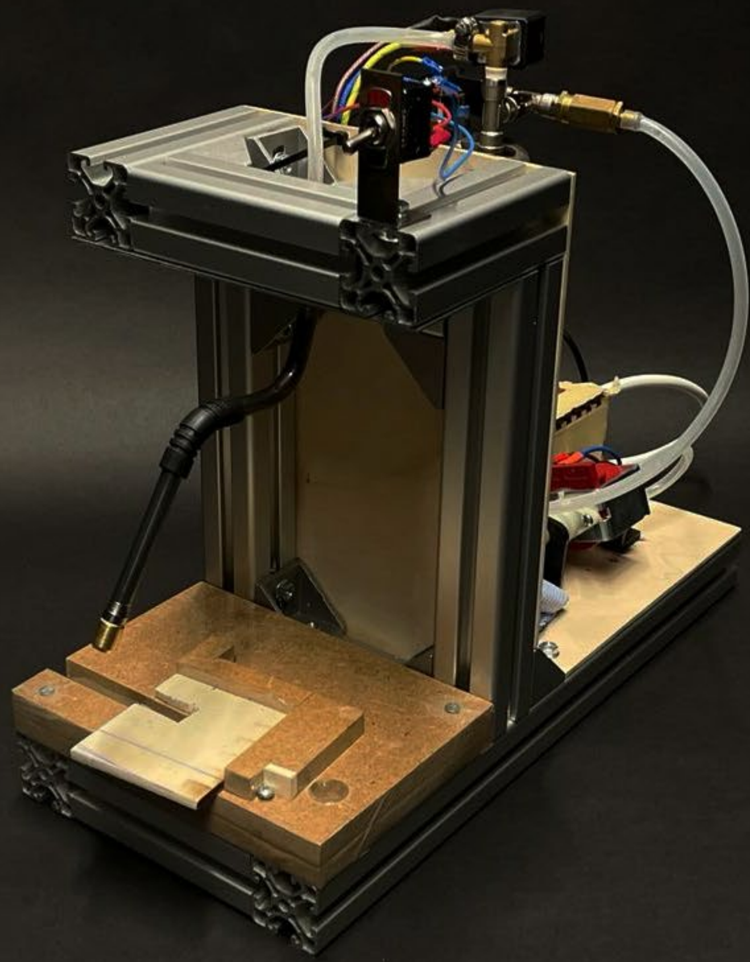
Creation of a stand-alone milk steamer for home use



Master thesis

Integrated Product Design – TU Delft

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Preface

Wow, what a journey this has been. I have completed my educational programme at the Delft University of Technology. This has been almost seven years in the making. During my time in Delft I have had the pleasure of working with incredible people, many of whom I may now call my friends. In these years, I have had the countless opportunities to participate in very diverse design projects which helped me to create a diverse set of design skills. Soon, I hope to implement these skills in the 'real world'.

When I started in Delft, I dreamt of creating the products that, before that had only existed in my head. The bachelor programme, but especially the master program of Integrated Product Design taught how to turn my dreams into a reality. With this in mind, I hope that this project is the start of a new journey: developing and producing my very first project. An adventure which I am very much looking forward to!

This project was not completed completely solo, therefore I think it is important to say thanks to everyone who helped.

First of all to my supervisory board, Ruud van Heur and Martin Verwaal: Thank you for trusting me in this project. I know that it was difficult to follow my progress during this project. At the important points you were there for me with words of reassurance and critical questions that re-lit the fire of curiosity.

Second of all thank you to the many people that offered me with their time, knowledge and even by providing me with parts for the many prototypes of this project. Thank you Didi, Marten, Peter, Rob, Katja, Sijmen, Jan Willem, Roos and Shervin. Without your contribution, the project might have had a very different outcome.

A very special thanks goes out to the personnel working at the PMB workplace. Your help allowed me to build the splendid prototypes that are on display in this project. By doing so, you have taught even more manufacturing skills that hopefully will prove very valuable in the future.

Lastly, thank you to my friends, family and loving girlfriend for supporting me throughout this rollercoaster called graduation. When I felt down, you always found a way to cheer me up and continue my journey. Also thank you for the many times you offered to help me during the project, this was always very much appreciated.

For you, dear reader, I hope you will enjoy the reading of the thesis as much as I have appreciated the project. Hopefully, you will one day see the rough diamond of this project as a cut diamond on the shelves of coffee equipment stores.

Now it is time for me to sign off by mentioning the last thing there is to say: Thank god, finally I am an engineer!

Jeppe

Executive summary

Coffee, a beverage consumed by nearly every (young) adult on this planet. Black gold, the drink that keeps you awake and gets you through the day. Whatever the occasion, coffee is always there to accompany you. Coffee drinks consumed out of house are most often consumed with the addition of milk foam. The addition of milk fundamentally alters the sensory experience of coffee, it reduces bitterness, astringency and adds a degree of sweetness. Frothed milk especially enhances the texture and overall mouthfeel of the drink, contributing to a luxurious and novel sensory experience.

This luxurious feeling is especially present when consuming the drink, served with beautiful latte art, in a café. At home, this luxurious feeling is far from achieved by many people. Most often, the coffee drinks with milk are served with thick, airy and dull foam. An affordable product that can reproduce café quality milk from the comfort of your home currently not offered.

The need for such a product was identified during the master elective Build Your Start-up at the Delft University of Technology. This thesis aims to develop a working prototype of stand-alone milk steamer for coffee enthusiasts that allows them to create café quality milk foam at home. The results of this thesis will serve as a starting point for the further development to one day be used by many people around the globe.

During this project, the target group for such a product was formed and product wishes were identified through user research, market analysis and expert interviews. These wishes were combined to identify the required theoretical knowledge about milk foaming and foaming technologies for the further development of prototypes.

Fluid and thermodynamics models were created to aid the identification of promising technologies. Three heating technologies were identified that could showed promise for the creation of a stand-alone milk steamer. These technologies were evaluated using physical prototypes. Eventually, custom nozzles were designed to complete the prototypes. These prototypes were evaluated with experts and deemed very capable of reproducing café quality milk foam.

The final prototype that is revealed during the final presentation will serve as a prototype that serves multiple purposes. It serves as a technology demonstrator which can be further developed. Furthermore, it can be used as a tool to gather funds for the further development of the concept. All with the goal of eventually manufacturing and shipping a product to many customers.

Contents

01.

Thesis introduction

The first chapter of this thesis describes the reasons for the initiation of this project. The current understanding of the problem of milk foaming at home is stated followed by the scope and approach of this project.

1.1 Project introduction

The global coffee market is growing massively since corona pandemic. Especially the premium coffee market has seen a big jump in demand over the last few years. Espresso based milk drinks are very popular in cafes, however, at home people do not consume milk drinks that frequently. A recent study by of ANP Pers Support (2022) shows that the most popular variety of coffee consumed at home in The Netherlands still is a regular black coffee. That might change in the years to come as World Coffee Portal (2023) states that people have invested heavily in high-end coffee equipment. This increase spending on coffee equipment started during the COVID-19 pandemic.

During the pandemic, many people were forced to work from home. People most likely noticed that the coffee that they could prepare at home was not on par with the coffee they consumed before the pandemic. As the most consumed drink out-of-house are milk drinks, it is expected that this spending was in part on the ability to create milk froth at home. This might change the most popular coffee drink at home from black coffee to a milk variant.

This growing interest in quality milk at home is also reflected in the increasing popularity of 'Latte Art Workshops' across various cafes in the country. Cafes hosting these workshops are often equipped with commercial espresso machines, valued at over €10.000, capable of producing the exceptionally high steaming power required to quickly produce silky smooth microfoam. However, such high-performance machines are currently not accessible to the average consumer at a reasonable price.

The market today reveals a noticeable price gap the products currently offered to consumers. The most notable difference: the foam quality. Creating silky smooth microfoam at home, like you are served in a café is currently rather difficult. During a master elective at the Delft University of Technology, it was identified that many people are looking for a solution to create café quality milk foam at home. Something that is not possible with a mechanical milk frother found in most households.

This presents an opportunity for a premium, yet reasonably priced product that can create café quality milk foam. This thesis aims to work towards the realisation of a stand-alone milk steamer that puts commercial espresso machine steaming performance in the hands of coffee enthusiasts who aspire to replicate café-quality beverages in the comfort of their homes.

Figure 1: Identified market gap for a high-end stand-alone milk steamer

1.2 Coffee in a nutshell

According to The Food and Agriculture Organization of the United Nations (n.d.), coffee is one of the most consumed an beloved beverages in the world and one of the most traded products globally. Although coffee has been a staple for many generations, its market continues to expand, partly driven by the growing interest of developed countries with specialty coffee and innovative coffee products. This chapter aims to describe the history of coffee, why we drink it in such large quantities, why people add milk to coffee and give insights into the culture of the coffee ecosystem.

1.2.1 History of coffee

Coffee traces its origins back to ancient Ethiopia, where it was first discovered around the 9th century. According to Pendergrast (2010), an Ethiopian goat herder named Kaldi first noticed the energizing effects of coffee when his goats became lively after eating coffee berries. This discovery marked the beginning of coffee's journey across the world. By the 17th century, coffee had made its way from the Middle East to Europe and was becoming popular across the continent.

Today, coffee has spread globally, with millions of people consuming it daily. Its popularity can be attributed to its unique flavour, cultural significance, and, notably, its stimulating effects, which increase alertness and concentration (Pendergrast, 2010).

The addition of milk to coffee is much later in time than the popularisation of coffee. Between 1787 and 1789 the people in Franc were introduced to the café au lait, which is warm coffee combined with warm milk (Thurston et al., 2013). From there on, coffee combined with milk evolved. With the invention of the Gaggia machine (1884, Italy), various formulations of espresso with milk (e.g., cappuccino and latte) spread in popularity to the UK (the 1950s), becoming more accessible than a regular espresso (Thurston et al., 2013). From the 1980s, the popularity of espresso based milk drinks spread to America and the rest of the world via coffeehouse chains (Pendergrast 2010).

1.2.2 Attraction of milk foam

The addition of milk to coffee is a practice influenced by various factors, including personal taste preferences, cultural norms, and the desire to modify coffee's natural flavour profile. In different regions, the choice of coffee drink reflects distinct cultural preferences. For example, in Italy, espresso is predominantly consumed without milk (Ozbun, 2023), whereas in Anglo-American coffee shops, a significant 80% of espresso beverages are served with milk (Thurston et al., 2013). This preference for espresso based milk drinks in cafes is confirmed by baristas in The Netherlands, they state that around 80% of the drinks they serve are espresso drinks with milk.

Figure 2: All espresso drinks with milk explained at Večerka in Brno, Pospisil (2023).

Milk fundamentally alters the sensory experience of coffee. It significantly impacts the drink's likability, as demonstrated by Li et al. (2014), and can change the preference for specific coffee blends (Cristovam et al., 2000). The addition of milk modifies the taste by reducing bitterness, astringency, and sourness, while adding a degree of sweetness (Narain et al., 2003; Niseteo et al., 2012; Gorman et al., 2021; Rashidinejad et al., 2021). Furthermore, the presence of milk in coffee can moderate caffeine's impact (Niseteo et al., 2012), rendering the drink more suitable for individuals who are more sensitive to caffeine's energizing effects.

The method of adding milk to coffee varies, from plain milk (either cold or heated) to frothed milk, which is a common addition in espresso-based drinks. Frothed milk enhances the texture and overall mouthfeel of the coffee, contributing to a luxurious and novel sensory experience. This aspect of coffee preparation, particularly the art of creating foam and latte art, adds a visual dimension to the beverage, enhancing its appeal and perceived value (Campbell & Mougeot, 1999).

1.3 Problem definition

In recent years, the culture of consuming coffee outside the home has led individuals to develop a taste for high-quality coffee beverages. This shift in consumer preferences has prompted significant advancements in home coffee brewing methods, such as the introduction of specialty coffee in the form of aluminium capsules. As a result, the quality of coffee that can be prepared at home has seen considerable improvements.

Sadly, this level of progress is not reflected in the domain of milk foam, with most of the households still using a mechanical frother. With such a milk frother, the results of the milk foam is usually thick and airy instead of the luxury fine foam found in cafes (Figure 3). Most of the milk foam created at home using a mechanical frother remains in the coffee cup after consumption. Besides that, thick foam does not allow for the pouring of latte art, a desire for many people demonstrated by the increasing popularity of Latte Art Workshops.

Figure 3: Difference between milk foam found in many households (left) and foam quality found in cafés (right).

Many consumers aspire to make smooth microfoam at home, for the enjoyment of creating beautiful latte art, but also since it enhances the sensory experience, its appeal and perceived value as mentioned in the previous chapter.

Lastly, current milk frothing technology that is within an acceptable price range for home use for many consumers, are plagued with problems such as milk overheating, foam being too thick, or the complete absence of foam.

With this information, we have identified that there is a gap in the ability to replicate café quality milk foam at home. This discrepancy highlights a significant shortfall in the home coffee experience and suggests a need for innovation. To do so, the following problem statement is formulated:

“Coffee enthusiasts must be enabled to reliably create café-quality milk foam at home, overcoming common issues with current technologies, thereby enhancing the overall quality and enjoyment of home-prepared espresso-based milk drinks”

1.4 Project approach

The project which inspired this thesis, was started in the master course Build Your Start-Up at the Delft University of Technology. In that course, the initial idea of improving the milk foam quality for people at home was quickly validated and a preliminary target group was identified. Having limited knowledge to build upon, this mean that this thesis takes place in the very first stages of the product development cycle.

Being this early in the design process means that there are many uncertainties. In order to successfully develop a product, first knowledge must be gathered on the user group, the market and the process of milk foaming. This information can be condensed into a list of requirements. The wishes and requirements from this list help to form the design goals and criteria for this project and product.

Only with this knowledge of the subject and the identified requirements it is possible to continue into the design and development stage, as it is important to make choices based on the stated requirements.

The structure of described previously very much resembles the double diamond framework. This framework was therefore chosen to follow during this thesis, however other methods and approaches are followed as a means to supplement the framework. A graphic representation of the project overview presented on the next page.

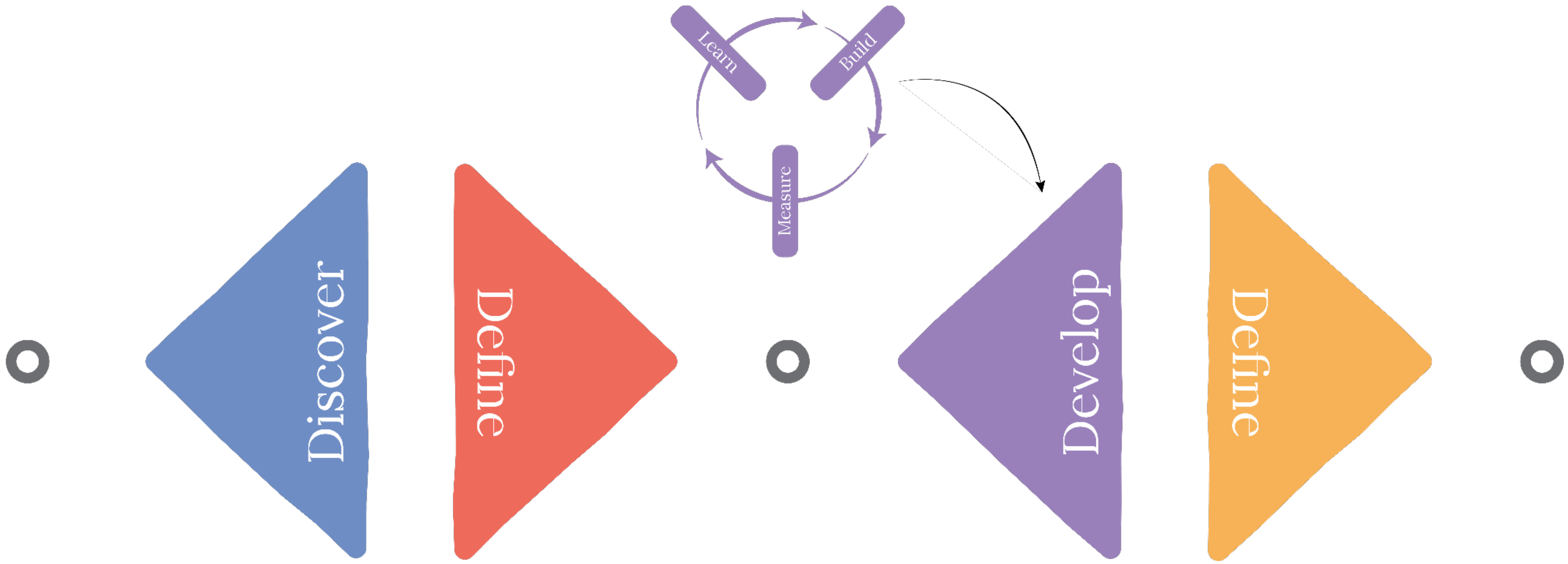
First quadrant aims to gather information of the context of this project by evaluating the current market for milk frothing appliances, identifying the proposition and product shortcomings. The target audience is further defined and a better understanding of their problem is created. This phase leads to the identification of possibilities within the market and several requirements for the new concept.

The second quadrant aims to refine the information and supplement it with more in depth information on foaming technologies. It aims to identify the most promising technology for the creation of milk foam by means comparing technologies found in current products and patent applications. The goal of this stage is to narrow down the design space and identify the requirements for the concept that must be developed.

In the third quadrant of the double diamond framework, concepts for the selected foaming technology must be developed and evaluated. To do so in a quick manner, the Lean Start-up approach as described by Van Boeijen et al. (2020) was followed. The approach uses compact canvasses to quickly validate ideas using a build, measure and learn cycle. This cycle is suitable for this project as quick learning is necessary to create a concept for milk foaming within the timeframe of the project.

In the final quadrant of the project, all the output of previous stages is combined into design of a final hardware prototype. This prototype should demonstrate its ability to replicate the smooth milk foam found in cafés to be evaluated with experts. Furthermore, this project provide insights into the knowledge gathered during this design process to aid further development of the concept.

1.5 Project overview



02.

Discover

This chapter aims to create a more holistic image of the market and the intended target audience of a stand-alone milk frother for home use. This is achieved by performing a competitor analysis and user group identification research.

2.1 Competitor analysis

2.1.1 Market analysis

Previously it has been described that there is has been little development of milk frothing kitchen appliances. The competitors consist of major players in the espresso machine market and a few innovative startups. The market the product should fit in is separated into two distinct categories: mechanical frothers and steam based frothers (Figure 4).

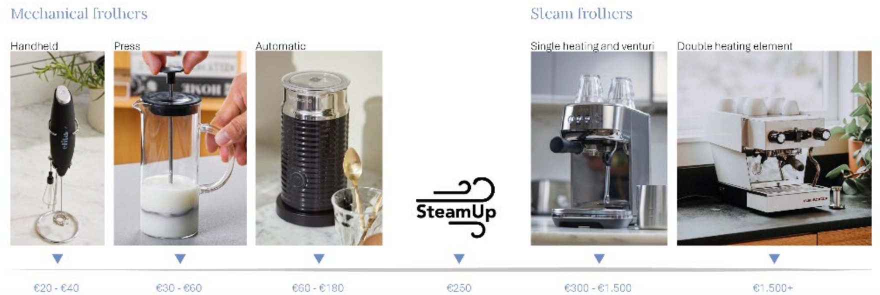


Figure 4: Two categories of milk frothers currently available

Mechanical frothers create milk foam by introducing mechanical work to the milk. Most often this work is done by a rotating mechanical component inside the milk jug and can be either handheld or automatic. In coffee forums, another method is mentioned by coffee aficionados: using a French press to make milk foam. This requires the user to separately heat the milk before frothing, which is often done in the microwave. This adds to the complexity of the process and therefore sees less implementation than automatic mechanical frothers.

The most commonly found frothers in this category are automatic mechanical frothers like the Nespresso Aeroccino. These frothers simultaneously heat the milk and create the foam. Advantages of these products are: no skill required, press and forget and of course the affordable price point However, this comes at the cost of milk foam quality, producing thick airy foams as they often overheat the milk, which is altering the flavour. Moreover, these products require extensive cleaning. Lastly, they are known to function properly for approximately 2-3 years, before needing replacement.

Steam based frothers rarely exist as standalone devices for home use, which means they often come attached to an espresso machine. Being attached to an espresso machine can be considered as a drawback as it means that the products will always be more expensive than mechanical frothers. Just as with mechanical frothers, this category either have manual of automatic modes of operation, with the most common being the manual steam wand usually found attached to espresso machines in cafés.

Within manual steam frothers we see a big difference in the scenario of usage between single and double heating element espresso machines. Single heating element espresso machines use the same heating element for both creating the espresso shot as frothing the milk. This reduces the costs of the device, but the heating elements are usually optimised for espresso, resulting in lower steaming pressure and lower quality milk foam. The quality, however, is usually better than mechanical frothers. Double heating element espresso machines have heating elements optimized for both espresso and milk frothing. These machines can often create the desired milk texture, but are rather expensive, with a starting price of €1500.

The value proposition of steam frothers is that it gives the user a barista feeling and the capability to create high quality milk foam with which latte art can be poured. However, manual steam frothers require the operator to have developed the skills to use this technology. According to baristas, it takes around 1 day of training to understand the basic principles, but finetuning the technique requires around 6 months.

In super automatic espresso machines and new offerings such as the Sage Bambino Plus milk is frothed automatically. The only thing required of the user is to provide the machine with milk. The working principle behind this milk frothing technology is discussed in paragraph 3.3.

2.1.2 Latest innovations

Recently, two stand-alone milk steamer (products similar to the proposed proposition of SteamUp) were launched on Kickstarter. As these products have a similar proposition, we can analyse their campaigns and learn about product aspects and features. It provides an insight into their view of the customer segment and the technology used. Furthermore, the comments of backers – people giving money for the possibility of receiving the first batch of product – can be analysed. From these comments we can extract product features, wishes and doubts, which provides useful insights into our potential customer segment.

Altogether, these two products are backed by 1089 people at the point of writing. This is a substantial amount of people buying into the value proposition of a innovative milk frothing product. During the BYS course, it was calculated that a first batch of 300 backers would be sufficient to cover the costs of starting production of the product. If the concept that is being developed can lead to approximately 500 customers, that would be a great start for the company.

The Meticulous Milk (Figure 5) was first announced on Kickstarter with the following proposal:

> *"Meticulous Milk is its own **standalone.device**, with a cutting-edge coil that heats a tiny bit of water almost instantly, no boiler necessary, no preheating required. It simply **makes. steam. on_demand**, letting you achieve **perfectly.textured.milk.in.seconds**. Texturing milk is hard, even for the most experienced baristas. That's why Meticulous Milk has sensors that **let. it. steam. milk. automatically**. Just choose your temperature and texture and a single button press gets you perfectly textured milk every time. Latte artist? Want to hone your skills? Meticulous Milk lets you **texture.milk.manually**, putting all the control in your hands."*

Figure 5: Product photo of the Meticulous Milk

Similarly to the Meticulous product, a few months later the Morning Dream was launched with a surprisingly similar proposition, target audience and design (Figure 6). Their proposal reads:

*"**No.matter.what.type.of.milk** you're using, or what type of drink you're making, our state-of-the-art technology ensures precise control over every aspect of the steaming process, resulting in the **smoothest.and. creamiest.milk** you've ever had **at.home**. Select what type of milk you're using, and the machine **automatically** selects the correct temperature and steam pressure for the best results. Our intuitive display **empowers. you. to. fine_tune** the machine's temperature and steam pressure to perfection. Whether you enjoy the convenience of capsule coffee or mastery of manual coffee brewing, The Morning Dream is the milk steaming solution that **coffee.enthusiasts** have been waiting for."*

Figure 6: Product photo of the Morning Dream stand-alone milk steamer

From these value propositions we learn that these products are aimed at both coffee enthusiasts as the general public, offering automated programs for easy operation and the ability to manually tweak and use the product as a traditional steam wand. They both highlight the perfect smooth texture, indicating that this is something consumers are looking for. The Morning Dream also mentions the of different types of milk, possibly indicating the use of plant-based milk alternatives. During user research it is interesting to find out what type of milk people use to prepare their milk drinks.

The comments from these campaigns (Appendix I) were analysed the mentioning of product and design features to complement the data from the questionnaire. The insights from this analysis are:

- Backers are interested in the quality of the product, comparing it to other high-end equipment in terms of functionality and durability.
- Some backers are concerned about the ease of use, including the ability to create a proper vortex for milk steaming, and the maintenance required for the machine.
- While innovative features are appreciated, there's a discussion about whether a simpler, more reliable manual-only unit would be preferable to a complex automatic one.
- Backers are interested in the programmable milk profiles for different types of milk, including plant-based options, indicating a demand for versatility and customization.
- The product should be easy to clean.
- Comments suggest a preference for a design that is both practical and visually appealing.
- Surprisingly, multiple people are interested in the maintenance requirements and the availability of spare parts of the product.

Personally, one comment caught my attention, it stated the following: 'Power sockets are limited in a kitchen, so a cord with piggyback connector would be appreciated. Meaning not only countertop space is limited, but so is the amount of sockets in the kitchen environment.

2.2 User group identification

Before starting this thesis, in the course Build Your Start-Up (BYS), the idea of SteamUp came to fruition. During this course SteamUp has identified their initial target group as: *'Coffee enthusiasts that use a manual lever espresso machine to create their coffee drinks at home'.* This is a very niche market, therefore it might be beneficial to identify whether there is a broader beachhead market for a stand-alone milk frother that can create café-quality milk foam.

Figure 7: Coffee set-up with products commonly found the set-up of people in the initial target group of SteamUp.

Most people that were interested in buying into the product promise of the SteamUp – a relatively affordable stand-alone milk steamer that offers similar steaming performance as commercial espresso machines – were people who had affinity of creating coffee drinks using commercial espresso machines. The product would allow them to implement their developed skills at home. This lead to a new hypothesis of a broader, beachhead market:

"(Aspiring) Home barista's that have (had) experience in making milk froth using professional machines, such as baristas and coffee enthusiasts that are looking to experience the preparation method of professional machines at home"

2.2.1 Questionnaire setup

A questionnaire was created to test the hypothesis about the revision of the target group. Furthermore it tries to understand the deeper problem of the target group and find out whether consists out of more aspects than just being unable to create high quality milk foam. The questionnaire also tries to identify product features that are desired by the target audience.

A questionnaire is a suitable method for gathering this data according to the User-Centred Design approach (Van Boeijen et al., 2009), as it allows the gathering of quantitative data from a large audience to see determine the share values and needs. After many iterations, the final questionnaire (see Appendix II) was created in Qualtrics and distributed to two different audiences – potential customers from the SteamUp sign-up list and the general public through LinkedIn.

Using LinkedIn makes use of the snowball effect to reach as many people as possible, allowing for the identification of people or groups of people that do experience the problem, but are not covered by the defined target audience.

2.2.2 Questionnaire results

The questionnaire was sent to the subscriber list of SteamUp, a list of 70 people who have actively expressed interest in the product promise and/or have placed a 'pre-order' resulted in 9 responses, even with an incentive given. This is a rather low response rate of just 13%.

The demographics of the respondents is rather interesting, as all respondents are male and fall mostly in the age group of 25-34 years old (Figure 8). Furthermore, half of the respondents are from Europe. Since most subscribers for the contact list of SteamUp were acquired through Reddit, a similar demographic to the user base of the platform was expected. This is the case, with the exception of the location of respondents, it was expected that most would be from the USA with around 50% of users residing there (Bianchi, 2024).

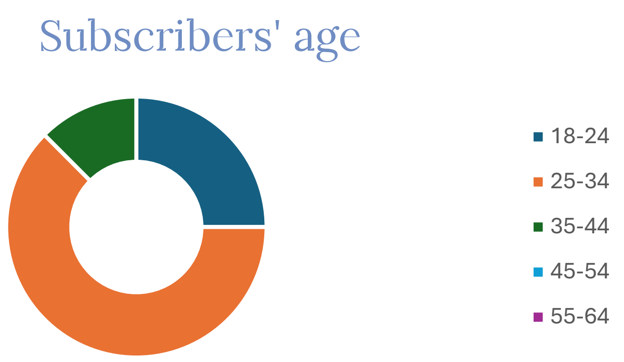


Figure 8: Demography of respondents of the questionnaire by subscribers of SteamUp

While there is a limited number of respondents, the responses paint a clear picture of the possible user group. All respondents would rate their experience with the preparation as hobbyist grade or are coffee professional.

Answers showed great similarity on preparation habits and requirements and wishes for the development of a new stand-alone frothing product. Most respondents (7 out of 9) have more than one product to create coffee drinks different kinds of coffee drinks. What is surprising about the results of the study is that the other two respondents only have the option to create pour-over coffee, which is not usually consumed with milk.

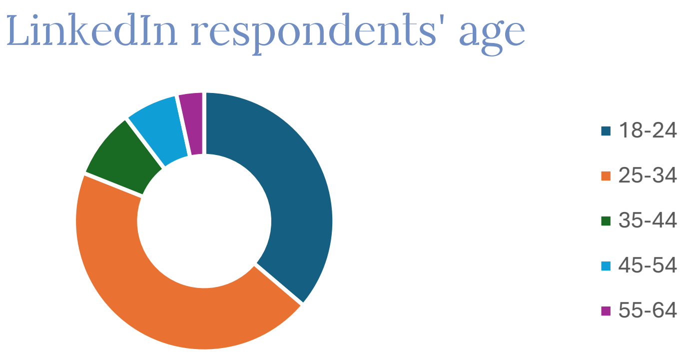
Almost all of the respondents use cow milk to create the milk foam, with only one respondent also mentioning plant-based milk alternatives. Furthermore, the quality of the milk foam they can currently create is described as microfoam with latte art by half of the respondents, about which they are moderately satisfied.

The problems currently faced by the people in our target audience are that the milk steamer that they use does not provide enough power and the inability to properly foam different types of milk. The lack of power also mans that the product has a slow heating time and the required aggressive vortex for the creation of microfoam is sometimes lacking.

The majority of the respondents were prepared to pay upwards of $200 dollars for a stand-alone milk steamer. The features that the target group is looking for in such a product are:

- Uses little counter space (6)
- To be in control of the foaming process (5)
- Provides a barista experience (5)
- Is easy to clean (4)
- Has the same performance as commercial espresso machine (4)

The questionnaire distributed through LinkedIn contributed to 62 responses, with slightly more female than male respondents. Age ranged from 18-64, but was concentrated in the age groups: 18-24 and 25-34.



From the data, it seems that there are no people that would fit the hypothesis about the target group. Still, there are a few interesting insights gathered from this data. Firstly, half of the respondents added milk (foam) to their coffee with a preference for cow milk. The most commonly used appliance for frothing milk is an automatic mechanical frother with the most stated reasons being the ability to foam automatically, short start-up and preparation time and the price point of the product. Lastly, half of the respondents want to improve their milk foam quality.

A product than can improve the quality of milk foam compared to their current frothing products are should have the following features:

- Must be easy to clean (14)
- Can foam every type of (alternative) milk well (13)
- I am in control of the foaming process (8),
- Is ready for use quickly (7)
- Uses little countertop space (7).

2.2.3 Community responses

Previously, during the course of Build Your Start-up, research about the product features of a stand-alone milk steamer was conducted with subscribers from the sign-up list of SteamUp. They stated the following reasons for looking for a different milk frothing solution:

- Current frother creates foam that is too thick to pour latte art
- Products that can provide the proper milk texture are not easy in use and do not perform consistently.

The product features and components of a stand-alone milk steamer that the respondents of the survey are looking for are:

Provide high pressure steam	Easy to clean
Removable water reservoir	Require small countertop area
Pressure gauge	Temperature control

2.2.4 Target group

Through the questionnaires sent to the sign-ups for the subscribers list on the SteamUp website and the market research, we have identified characteristics of the target audience. Furthermore, the information has given insights into the wishes of the target audience for a stand-alone milk frother.

The people in our target group can be described as coffee hobbyist and/or coffee professionals, also called coffee snobs. Coffee snobs have more than one way of making coffee, usually with an espresso focused machine at the centre of the setup. However, their setup lacks products that allow the user to make café quality milk foam simultaneous to the preparation of their espresso. To solve this problem, some people have started modifying their own espresso machine and there are people who have attempted to create their own – very dangerous - versions of stand-alone milk steamers.

The people in this target audience often have a dedicated location in their house for the preparation of coffee. This location often looks like the setup depicted in Figure 9, which is representative for the coffee setup of most people in our target audience.

Figure 9: Representation of the coffee setup of people in the target group (xylem-utopia, 2024)

The results from the questionnaire distributed to LinkedIn showed that many people are interested in improving. In the future, the market might expand into a wider audience. For now it seems that this will only happen if the technology can be made available at a very low price point.

2.2.5 Preferences

Combining the preferences gathered from all of the sources allows to for the creation of a list of the most important preferences that must be met during the development of the concept:

1. The product should be easy to clean
2. The product must give the user control over the foaming process
3. The product must be able to foam every time of (plant-based alternative) milk well
4. The product must use little countertop space
5. The product be ready for use quickly

03.

Define

This chapter aims to define all the requirements for the concept to be developed. It identifies these requirements through analysis of the intended use of the product, of milk foam quality and how to achieve it, commercial machine analysis and system modelling.

3.1 Product usage

The goal of the concept that is developed in this thesis is to create high quality milk foam for the creation of espresso drinks with milk. This means that the product must fit into the existing workflow of creating an espresso drink. This chapter aims to identify requirements for the usage of the concept that are determined by the types of drinks that will be created with it and the environment in which it will be used.

3.1.1 Types of drinks

The amount of milk required for the preparation of espresso based milk drinks is highly dependent on the type of drink and the location where the drink is served. Since the goal of the SteamUp is to allow (hobbyist) home baristas to prepare drink like they get in their café, we focus on the milk required to serve drinks according to modern espresso recipes.

The most common espresso based milk drinks in cafes are the espresso macchiato, cappuccino, cortado, flat white and latte macchiato. Recipes for these drinks will be dependent on the café that serves them, but according to Kasperowicz (2023) and Cooper (2023) the drinks can be roughly formulated as follows:

1. Espresso macchiato – 2 ounces
2. Cortado – 3 to 4 ounces
3. Cappuccino – 5 to 6 ounces (in cafes up to 8 ounces)
4. Flat white – 5-6 ounces
5. Latte macchiato – 8 ounces

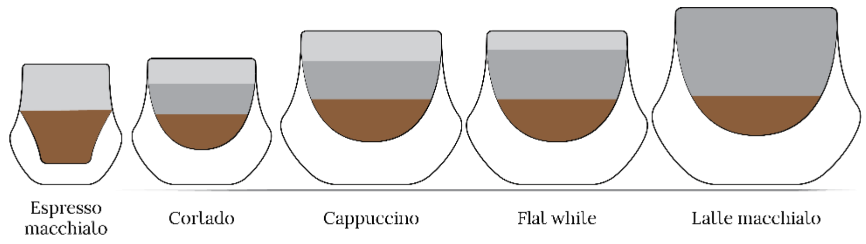


Figure 10: Representation of the ratios between espresso, milk and milk foam in the most served coffee drinks with milk.

While it is unsure whether US or imperial fluid ounces are used in the recipes, we can assume 1 ounce is roughly 30 ml. The largest drink of these recipes, the latte macchiato, requires around 6 ounces of steamed milk, which correlates to 180 ml of milk. Meaning roughly 360 ml of steamed milk is required to prepare two of these drinks at home.

3.1.2 Product environment

The consumer will probably use the product to froth milk simultaneous to the brewing of the espresso, which means both products require power. The combined use of these products should not exceed the power limit of one electricity group (3600W in the Netherlands). There are multiple ways to create suitable coffee drinks to turn into milk drinks, they require either a espresso machine or a electric kettle. Espresso machines typically consume between 1000 and 1500W (Raveling, 2023) and electric kettles that are often used by coffee hobbyist (Christensen, 2023) consume between 900 and 1500W, therefore the heating element power usage should not exceed 2000W.

3.2 Understanding foam

In the previous steps is has become apparent that high-quality milk foam is one of the key features of this product. Therefore, a deep understanding of (milk) foam is crucial for the success of this project.

Foaming is a process that involves mechanical agitation or gas injection to produce two distinct phases whereby the liquid continuous phase surrounds a dispersed gaseous phase. To make a foam, you need gas, water, energy and a surfactant. Energy to because interfacial area between the two phases is enlarged, free energy of the system increases. Surfactant provides mechanisms to prevent the coalescence of the newly formed bubbles. It also lowers interfacial tension and the Laplace pressure, facilitating breakup of bubbles into smaller ones (Walstra, 2003).

Milk foam is created when air is introduced to milk through mechanical agitation or gas injection. It is possible to foam milk because of the surfactants in it, casein (about 80%) and whey (about 20%). The milk proteins disperse well in water and possess both hydrophilic and hydrophobic groups, and the ability to reorientate these groups at the air-water interface. At the interfacial regions, the proteins unfold and rearrange the polar and nonpolar groups toward the aqueous and non-aqueous phases, respectively (Ho et al., 2021). This encases the air bubble with a thin-film layer, allowing it to remain in the liquid for an extended period of time. The mechanism of this process is demonstrated in Figure 11.

The whey protein is mostly important for lowering the surface tension between the air and the milk, important for the foam stability. Casein on the other hand is important for the functional property of foamability (Barista Hustle, 2023).

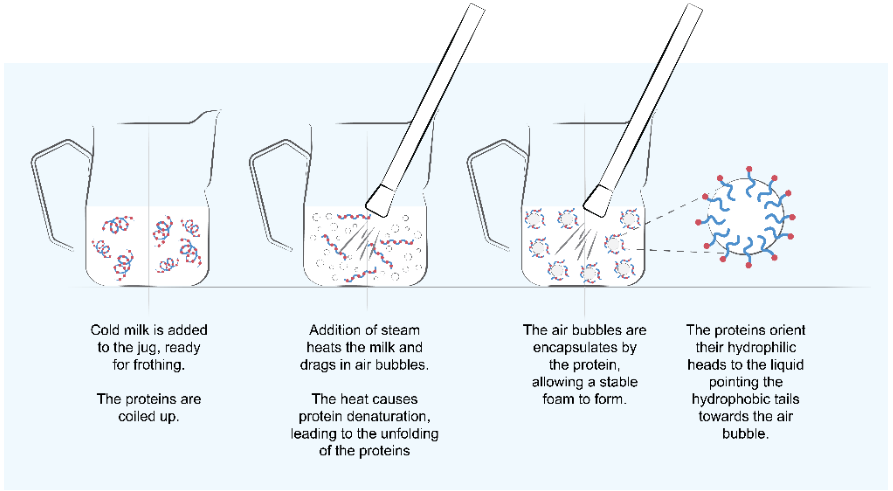


Figure 11: Protein behaviour during the milk frothing process.

3.2.1 Milk foam

Previously the desired texture of milk foam was describes as soft, microfoam and creamy. However, it is difficult to grasp what is meant by these terms. Therefore, this chapter aims to more scientifically describe what factors describe quality milk foam and tries to identify how this quality can be influenced by a milk frother.

After receiving an espresso based milk drink in a café, you generally expect the foam; to have a pleasant texture, to retain at least some volume for the duration of the consumption and as a bonus beautiful latte art. However, Huppertz (2010) mentions that some most important parameters for the scientific evaluation of milk foams to be foamability, foam stability and air bubble size.

Foamability also referred to as Steam Frothing Value (SFV), refers to the ability of milk to foam and is easily determined as the volume of foam formed from a given quantity of milk (Huppertz, 2010). Foamability can be calculated with the following formula:

$$SFV = \frac{Tv - Lv}{Lv} \times 100$$

Tv is the total volume of liquid plus froth, whereas Lv is the liquid volume of the milk, both measured at a known time after preparation, typically 3 minutes (Rampini et al., 2007). Foamability is directly linked to the amount of air introduced and the ability of the proteins to hold onto this air once the foam has formed (Marinova et al., 2009).

Foam stability refers to the resistance of the foam to collapse. Over time air bubbles can combine to form larger bubbles and eventually get so big that the bubbles burst, which reduces the volume of foam. Foam stability for the creation of milk foam in coffee drinks is sufficient when the foam can retain most of its volume during the typical consumption time – approximately 15 minutes - of such a drink.

Air bubble size is related to the average size and distribution of air bubbles in the foam. Determination of air bubble size as a function of storage time can give insights into the resistance of the foam bubbles to disproportionation and coalescence. Air bubble size is not only important to the stability of foam, but it is also a big determining factor of the sensory evaluation of foams. The smaller the average size of air bubbles is foam, the more stable the foam is and smaller bubbles are often associated with soft texture.

The maximum stable bubble diameter is based on the dimensionless Weber number. Evans et al. (1992) have demonstrated that the maximum stable bubble diameter can be determined by the following equation:

$$d_m = \frac{We_{cr} * \sigma}{\rho * \bar{u}^2}$$

- d_m = maximum bubble diameter
- We_{cr} = critical Weber number
- σ = surface tension of the liquid
- ρ = density of the liquid
- u = average of squares of the velocity differences in the vicinity of the bubbles

In systems with a turbulent flow regime, the critical Weber number is between 1.18 and 1.20 and Walstra (2003) has shown that, it can be expected that foams are in a turbulent flow regime.

Varley (1995) discovered that bubble size decreases as fluid velocity increases, this is only the case when the entrainment ratio (ER) stays the same. Ensuring high turbulence without the further entrainment of air will be a challenge, especially for inexperienced (home)baristas.

Temperature is another key factor in milk frothing, impacting foamability and foam stability. Foamability and stability are minimal below 35 °C, improving significantly at temperatures of 45 °C or higher. This change is attributed to the fat in milk being partially crystalline at lower temperatures. Foam stability is optimal between 55 and 65 °C, as indicated by Kamath et al. (2008). However, Klimanova et al. (2022) advise against exceeding 60 °C to prevent whey protein denaturation, negatively impacting foam properties and taste.

Addition of water is believed to be responsible for the poor frothing behaviour of some milks. The results of research conducted by Deeth & Smith (1983) contradict this believe. Very little change in foamability was observed with up to 15% addition of water. In fact, the amount of foam relative to the milk content actually increased when water was added.

Addition of water to the drink, can however change the organoleptic properties of the milk.

Concluding, the quality of milk foam can be best described by three properties; foamability, foam stability and air bubble size. These factors are easy to visually determine. To guarantee proper milk foam, the temperature of the milk should be between 55 and 65°C. Furthermore, concept must be able to introduce enough air to create the proper volume of milk. Lastly, the addition of water may not exceed 15%, to guarantee proper foamability. Preferably, addition of water is minimized as this might impact the drinks flavour.

3.2.2 Plant-based milk alternatives

In recent years, we have seen growing demand for plant-based alternatives to milk. Half of the coffee drinkers claimed that they drink plant-based coffees out of home in 2020 (Grant, 2020). Most people choose these plant-based alternatives because of health trends, allergen concerns (McCarthy et al., 2017) and environmental concerns (Haas et al., 2019). For the development of a stand alone milk frother, it is important to understand the physical and organoleptic differences.

Plant-based alternatives to cow milk have chemical differences to cow milk, such as the proteins they contain. However, manufacturers of these alternatives try to mimic the foaming properties of cow milk. This should allow for ease of use by means of little adjustment. Zakidou et al. (2022) demonstrated that soy and coconut show rather similar foaming properties to full-fat UHT cow milk. The oat drink could not reproduce cow milk foaming properties, but is not far off.

Recent guides on frothing milk alternatives paint a different picture. Grant (2020) mentions that these alternatives have to be prepared rather differently. From his "Guide To Working With Plant Milks" he states the properties of the 4 most consumed plant-based milk alternatives, which is summarized in Figure 12. As a rule of thumb, alternative milks generally should not be heated above 55°C, as this changes the foaming properties and sensory properties such as the sweetness for worse (Mridul, 2022).

A difference in bubble size of foams between plant-based alternatives and dairy milk was observed while visiting cafes. The foams created with the plant-based alternatives usually showed visible bubbles, while foams formed with dairy milk usually consisted out of smooth microfoam without visible bubbles.

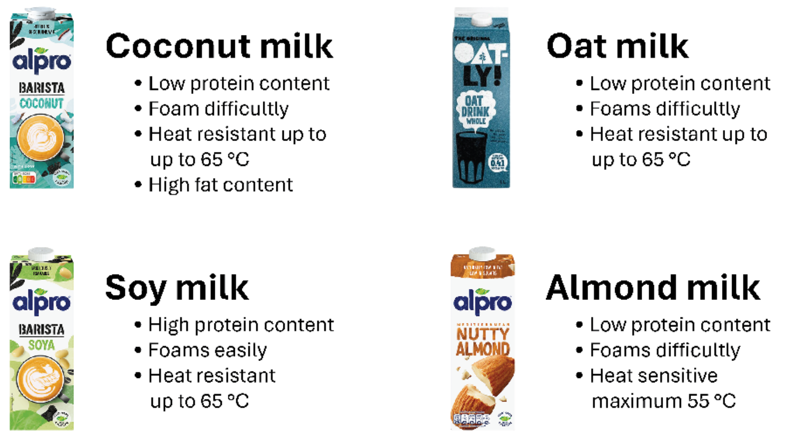


Figure 12: Plant-based milk alternatives with their respective frothing requirements

The physical properties are one factor of the (alternative) milk foam, the other is the organoleptic properties experienced by the consumers. Zakidou et al. (2022) have performed a sensory analysis of the aforementioned plant-based alternatives, demonstrating similar colour, gloss and texture for most drinks. The taste of the alternatives are different; soy was perceived to taste significantly worse than cow milk, coconut scored similar to soy, while oat was somewhere in between.

Please note that due to the recent popularity, these plant-based milk alternatives are being intensively developed and improved. This means that papers of a few years old might be outdated already. Next to that, different brands make the same 'type' of milk alternative, by a different recipe, which could mean different frothing characteristics making an absolute comparison rather difficult.

Generally, plant-based milk alternatives should be foamed to the same temperature to cow milk, with the exception of almond milk. Most milk alternatives have lower protein contents than milk, therefore it is important to introduce more air when frothing. Soy however, has a very high protein content requiring less air.

Although the foaming process is still different to cow milk, it is important to constantly evaluate the properties of improved recipes for plant-based alternative milk to guarantee proper milk foam quality.

3.2.3 Expert opinion

Next to theoretical knowledge, the best place to gather information about milk foam quality and how to create it is by turning to experts. These experts were found in rules and regulations, barista training materials and interviews with baristas.

Expert interviews conducted with baristas of 3 cafes offering latte art workshops in the vicinity of Delft (Appendix III). During the interview, the following subjects were discussed: what they think high quality milk foam is, what they pay attention to during the frothing process. Experts were also asked about their opinion about frothing with the machines available to consumers and the interview was concluded with the question what features they ought important for a stand-alone milk frother.

All three sources shared similar views on the properties of perfect milk foam. These properties are considered to be the standard for all types of milk (alternatives), the only thing that should be different should be the taste of the milk itself. The properties for perfect milk foam are the following:

- The volume of the mixture of milk and foam must reach between 130 and 150% of the starting volume.
- Bubbles in the foam may not be visible to the naked eye.
- The temperature of the milk and foam mixture must be between 55 and 65 degrees Celsius.
- The foam must be stable for the nominal duration of consumption of espresso-based milk drinks.
- The foam must have a glossy surface finish.

The baristas in the expert interviews mentioned the following properties for the development of the concept of a stand-alone milk frother. These wishes can be considered during the development phase in component selection and prototype evaluation

1. Product should have a short start-up time.
2. Must be able to create milk foam for 2 drinks at once
3. When using steam
    a. Full power output should be instant
    b. Provide adjustability of pressure
        i. Higher than consumer espresso machines, lower than commercial espresso machines.
    c. Allow modification of steaming nozzles.

3.2.4 Conclusion

In this chapter, the characteristics of café quality milk foam have been identified. With that, some influencing factors for these characteristics are also identified. Café quality is described and influenced as follows:

- The volume of the mixture of milk and foam must reach between 130 and 150% of the starting volume.
  - Product must entrain enough air to form the bubbles
- Bubbles in the foam may not be visible to the naked eye.
  - Provide high fluid velocity while refraining from adding additional air.
- The temperature of the milk and foam mixture must be between 55 and 65 °C with the exception of almond milk.
- The foam must be stable for the nominal duration of consumption of espresso-based milk drinks.
- The foam must have a glossy surface finish.

Some wishes for a stand-alone milk frother are identified as having a low start-up time, being able to froth milk for two drinks simultaneously and providing product adaptability.

3.3 Foaming technologies

Milk foam can be created using a variety of techniques, such as milk powders that form a foam through a chemical reaction with water and technologies to add energy to form a foam in milk. This paragraph will analyse different technologies through market analysis: mechanical agitation, direct steam injection and venturi based systems in the context of the target group. The aim is to identify the suitable technology for the creation of the foam quality described in the previous chapter.

Different technologies for milk foaming result in different bubble sizes (Jimenez-Junca et al., 2015; Völp et al., 2021). Steam injection has a mean Sauter radius of 150-180µm, whereas milk foam created with mechanical agitation products have a mean Sauter radius nearly double of that, between 200 and 300µm. Passive venturi nozzle creates foam bubbles with a diameter between 170 and 260µm. Data on active control venturi ejectors is not available in literature.

With the knowledge of the maximum stable bubble diameter, we can also determine the Sauter mean diameter of the foam and the other way around. The average value for the bubble diameter ratio d_{vs}/d_m from experimentation is 0.61, which is in agreement with other published numbers (0.60-0.62) Evans et al. (1992).

3.3.1 Mechanical agitation

Mechanical agitation is the most common method of producing milk foams. This technology is mostly used in homes, because of the low price and ease of use. The application of mechanical agitation for the creation of milk foam at home has several advantages and disadvantages as depicted in Table 1.

Table 1: Advantages and disadvantages of mechanical agitation.

Advantages	Disadvantages
Control over foaming	Separate heating and foaming
Small form factor	Difficult to clean
Low price	Requires more cleanup
No milk dilution	Might not achieve café quality milk foam
	Short life span

While the base technology is the same for adding air to the milk, we distinguish two different types of mechanical agitation, manual and automatic. Examples of both manual and automatic mechanical agitation products are shown in Figure 13.

Figure 13: Different types of mechanical frothers, from left to right: French press, handheld electric frother, automatic frother

Mechanical agitation introduces air to the milk by violently moving the milk, entrapping air in the milk. This is usually performed by rotating whisks of different designs or fine a fine mesh that is moved up and down however, the most recent innovation (Figure 13, product in the middle) is the combination of an impeller combined with a fine mesh screen. The rotation of the whisk creates a vortex within the vessel which is important for incorporating liquid between the air bubbles and reducing air bubble size. The steps for creating milk froth using mechanical agitation are displayed in Figure 14.

In the context of the target audience of this project, the application of mechanical agitation would in the form of manual mechanical agitation, since this is the only way the user is directly in control of the process creating the foam.

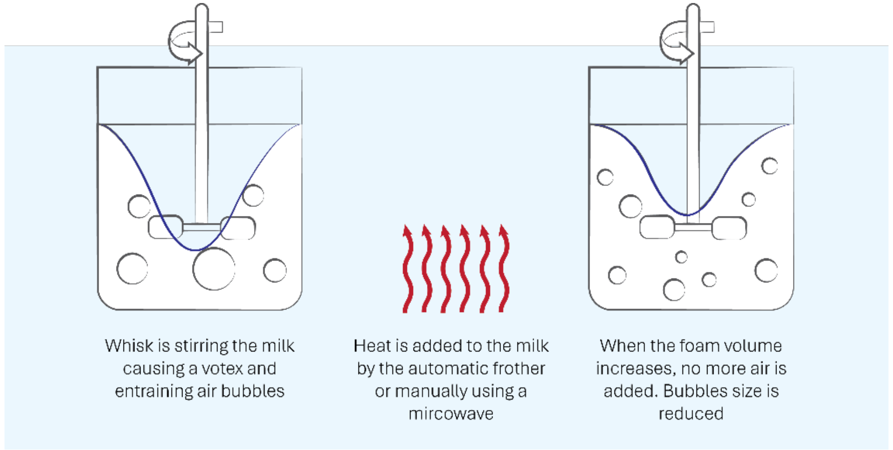


Figure 14: process of milk foaming by mechanical agitation

3.3.2 Steam injection

Steam injection is the most traditional technology used for making milk foam and has been around since the invention of espresso machines. This technology has been at the heart of every café ever since, preparing millions of espresso-based milk drinks daily. This technology uses steam – usually generated in boilers to heat the milk, while introducing air at the same time. When used correctly, a steam wand changes cold milk into warm steamed milk in the steps shown in Figure 15.

In cafes, it requires a trained barista to operate the steam wand correctly. According to baristas, it takes about 6 months to master the steam wand with the proper technique. The technology of steam injection has not changed much through the years, but we have seen the implementation of this technology at lower price points than professional machines. The differences between these machines manifest mostly in the steam flow rate of each of the systems.

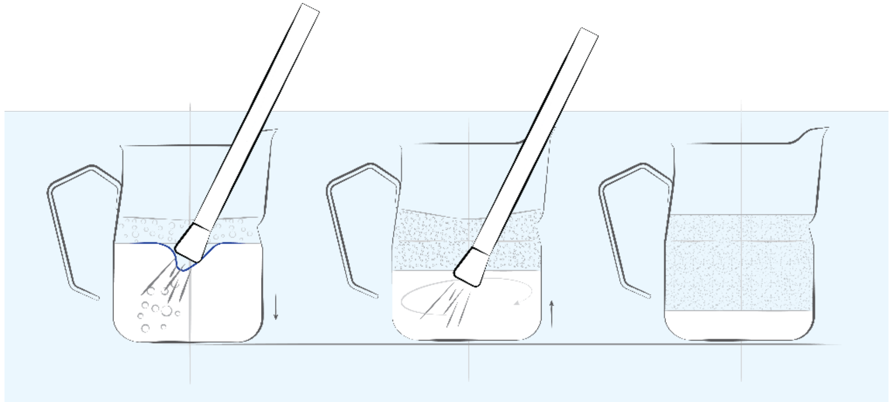


Figure 15: Process of foaming using steam injection

Jimenez-Junca et al. (2015) showed that increased steam pressure decreases the time needed to generate foams, while enhancing their foamability, stability, and texture. This confirms the desire of high steam pressures, comparable to that of espresso machines at home. While maximum bubble size exceeds the 200 μm threshold in the requirements by 45 μm, it is the closest to the desired situation. Furthermore, the test was executed using a consumer model espresso machine and the test has been standardized leading to higher bubbles sizes in comparison to commercial machines operated by baristas.

To conclude, the application of mechanical agitation for the creation of milk foam at home has several advantages and disadvantages as depicted in Table 2.

Table 2: Advantages and disadvantages of steam injection.

Advantage	Disadvantage
Control over foaming	Might have long start-up time
Easy to clean	Skill required to operate
Long life span with proper maintenance	Dilutes milk
Can create café quality milk foam	Expensive
Offers barista experience	Large form factor

3.3.3 Venturi injector

Milk foaming using a venturi injector has seen many innovations. The technology uses a venturi ejector to combine steam and air (Figure 16). The venturi effect happens when a fluid or gas flows through a constricted section, causing a reduction in fluid pressure in this constricted section. This creates suction at the constricted section, allowing for gas or a fluid (this instance air) to be drawn into steam flow.

In the context of the target audience, there are two different approaches of implementing venturi ejectors in a milk foaming product: active air addition and passive air addition. A process of passive air injection is described in WO2020103311A1, where air is pulled into the venturi by opening a valve. The process of active air injection is described in AU2019206066B2, this attaches an air pump to the venturi valve allowing the machine to determine exactly how much air is being injected into the foam.

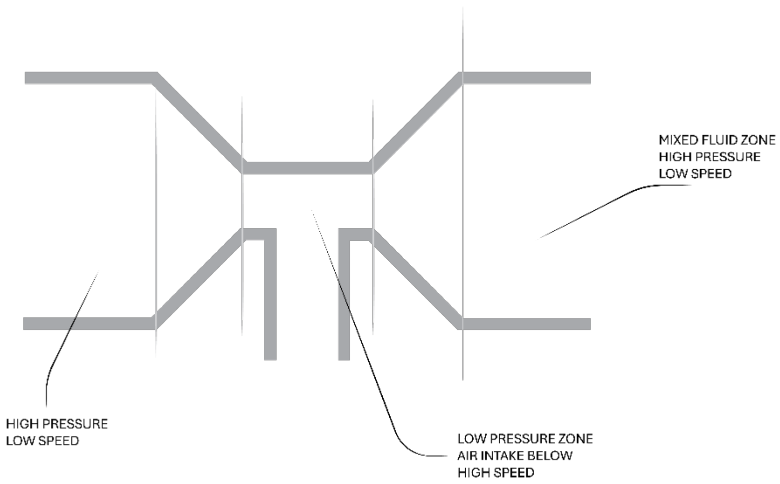


Figure 16: Venturi principle with the characteristics for each zone.

Summarizing, the application of a venturi injector for the creation of milk foam at home has several advantages and disadvantages as depicted in Table 3.

Table 3: Advantages and disadvantages of venturi injectors

Advantage	Disadvantage
Control over foaming	Might have long start-up time
Easy to clean	Dilutes milk
Can possibly create café quality milk foam	Increased complexity
Offers part of barista experience	Expensive
Skill required to operate	Lifespan unknown
	Large form factor

3.3.4 Technology choice

Based on the advantages and disadvantages of the three technologies in the comparison, the choice was made to develop a milk frother that makes use of traditional steam injection.

The was mostly motivated by the requirement of maximum bubble size, of which direct steam injection seems to be the only technology to be proven to meet this requirement. While it might be possible to achieve the desired texture through extensive development of the venturi principle, there are a few reasons to not select this technology.

Firstly, the addition of an active or passive venturi system increases the complexity and cost of the product. While steam based frothers are already rather expensive, this is not desirable. Another reason is that the application of the venturi principle in this context is relatively new, therefore it is unknown what the lifespan of these products will be, a question that is unanswered is how much is a venturi affected by limescale build-up.

A minor, yet final reason to select direct steam injection lies in the experience of the technology. People in our target group are familiar with the technology, requiring little adjustment. In the development it is important to address the disadvantages posed by direct steam injection such as dilution and reduced power found in consumer machines.

As a final remark, the venturi principle is interesting to further investigate as a technology aimed at people not experienced with commercial espresso machines. The pitcher with milk can be placed down on a surface. The only thing the user has to worry about is the starting and halting of air injection. While minimal, this could still give the user the barista experience and a feeling of accomplishment.

3.4 Understanding steam

For the identification of heating elements it is important to have a basic understanding of steam. Steam, a vital component in numerous industrial and commercial applications, exists in three primary forms: unsaturated steam, saturated steam, and superheated steam. Each type possesses distinct characteristics, applications, advantages, and disadvantages, especially when considering aspects of heating, dryness, and steam flow.

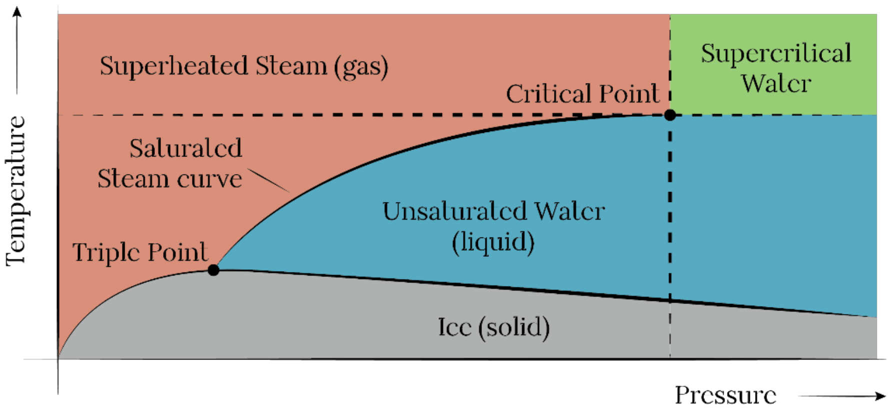


Figure 17: States of water and steam based on temperature and pressure.

3.4.1 Types of steam

Saturated steam is steam at its boiling point for a given pressure, without water droplets, making it entirely in the gas phase. Produced when water is heated in a closed container until an equilibrium is established, it's widely used in power generation, sterilization, and cooking. Saturated steam's advantage is its high heat capacity and efficiency in transferring energy. However, its temperature is limited to its boiling point at a given pressure, and it can cause scaling and corrosion in equipment if not properly maintained.

Superheated steam is achieved by heating saturated steam above its boiling point, superheated steam exists solely as a gas, with no water content. It is commonly used in turbines for electricity generation, drying processes and chemical manufacturing. The key advantage of superheated steam is the higher energy content compared to saturated steam, resulting in reduced condensation in steam pipes. On the downside, it requires more energy to produce and can be more destructive to equipment over time due to its higher temperatures.

Unsaturated steam, also known as wet steam, this type contains water droplets within it. Unsaturated steam is common in heating systems where complete vaporization is not achieved, including boilers. In the context of this project unsaturated steam is very undesirable as it waters down the milk and therefore might change the flavour of the coffee. However, it must be noted that creating perfectly saturated steam is almost impossible.

Saturated and super heated steam could both be desirable options for this application. Superheated steam due to its dryness, however it requires more energy to create, reducing the maximum possible flow. Saturated steam is desirable due to its balance between the energy requirement for creating the steam and dryness. However, it must be noted that in partly open systems without steam traps, saturated steam is nearly never achieved due to condensation in the piping.

Super heated steam requires more energy create, but it has the advantage that during the transport of this type of steam through piping, energy is lost, but no condensate is formed. This means that using super heated steam in a milk frother, there is less dilution of the drink.

3.5 System modelling

Steam is utilized to heat the fluid to be foamed. Using the laws of thermodynamics, the energy required to heat the fluid can be determined. This data could be combined with insights from the commercial machine test and physical chemistry research, allowing the identification of system parameters for the list of requirements. To do so, a theoretical model (Appendix IV) of fluid- and thermodynamics is drawn up based the system representation of Figure 18. This system representation includes all the parts that come in contact with the water required to generate steam in the product.

The theoretical system model is constructed in four steps, in this model the system is assumed to generate perfectly dry steam:

1. Calculate the amount of energy required per second based on commercial machine performance evaluation.
2. The mass flow of the system is determined using the equation for steam flow through an orifice stated (TLV CO., LTD., n.d.). This equation depends on important system variables that can be influenced in the design of the concept.
    a. Pressure or temperature of the steam, either can be used since the pressure and temperature of saturated steam are dependent variables.
    b. Discharge coefficient: a constant determined by the geometry and surface finish of the orifice.
    c. Area of the nozzle opening
3. Heat losses for the system are calculated minimizing this is the design of the product is recommended, the losses depend on:
    a. Temperature of both heating element and parts after heating elements
    b. Area of parts in contact with surrounding material, liquid or gas
    c. Convective and heat transfer coefficient
    d. Emissivity value of the material of the parts
4. Finally, the power requirement from the system can be calculated.

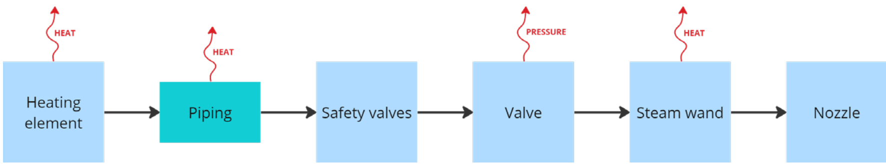


Figure 18: System model, zoomed in on the components in contact with steam

3.5.1 Conclusion

From this model we can determine the machine characteristics that influence the steaming performance. These characteristics must be further researched and optimized during the develop phase:

- Pressure or temperature of the steam
- Area of nozzle opening
- Length and material of piping

It must be noted that if super heated steam is used, the current model cannot predict the system behaviour, because pressure and temperature are not dependent variables in super heated steam.

3.6 Café machine evaluation

Commercial espresso machines are the backbone of cafes around the world. They create the quality drinks coffee enthusiasts around the world try replicate at home. To do so, these enthusiasts require a milk steamer with similar steaming performance as the commercial espresso machines. Designing such a product requires insights into what exactly entails steaming performance. To be able to design for this, it is of critical importance to get an understanding of the performance indicators of these machines. Important machine characteristics that influence the quality of milk froth are previously identified:

- Pressure of the steam: this determines the speed and temperature of the steam
- Dryness: although subject to debate, dryness can influence the flavour of the beverage by potentially diluting it.
- Steam flow rate: this determines how fast the milk is heated

These performance factors may be subject to the influence of machine features such as heating element size and power, piping material and insulation, steam wand type, and steam wand nozzle geometry.

3.6.1 Study design

The objective of this study is to document the performance indicators of commercial devices, so that it can be determined whether these same characteristics can be achieved in a design for a consumer product. The test has been devised to record the three machine characteristics mentioned previously that influence the quality of the milk foam.

There already exists a Dutch norm (NEN-EN-IEC 60661:2014 see Appendix V), which describes the methods for measuring the performance of electric household coffee makers.

The test is largely the same as the norm, but differs in the following ways:

- Container used to hold the liquid to be frothed as a similar vessel could not be identified for purchase.
- In the test, water is used with a drop of dish soap to simulate milk frothing without food waste.
- Dish soap was added in the test of heating ability to supress unwanted screeching of the steam wand.
- The part of testing the heating ability, was not conducted for 120 seconds, but until the water and dish soap mixture was about to overflow the container.
- An extra part was added to the research to measure the volumetric flow rate of the machine and the temperature of the steam.
- Machine characteristics such as boiler pressure and steam wand nozzle hole information was recorded.

With all the changes mentioned above, the study is conducted in two parts. The test is divided into two parts. The step-by-step description of the research can be found in Appendix VI.

In the initial phase of study, water is subjected to the steaming process as described in the NEN-norm. The temperature is the water is recorded as well as the water adsorption during the process. Figure 19 shows the performance test being executed in this phase.

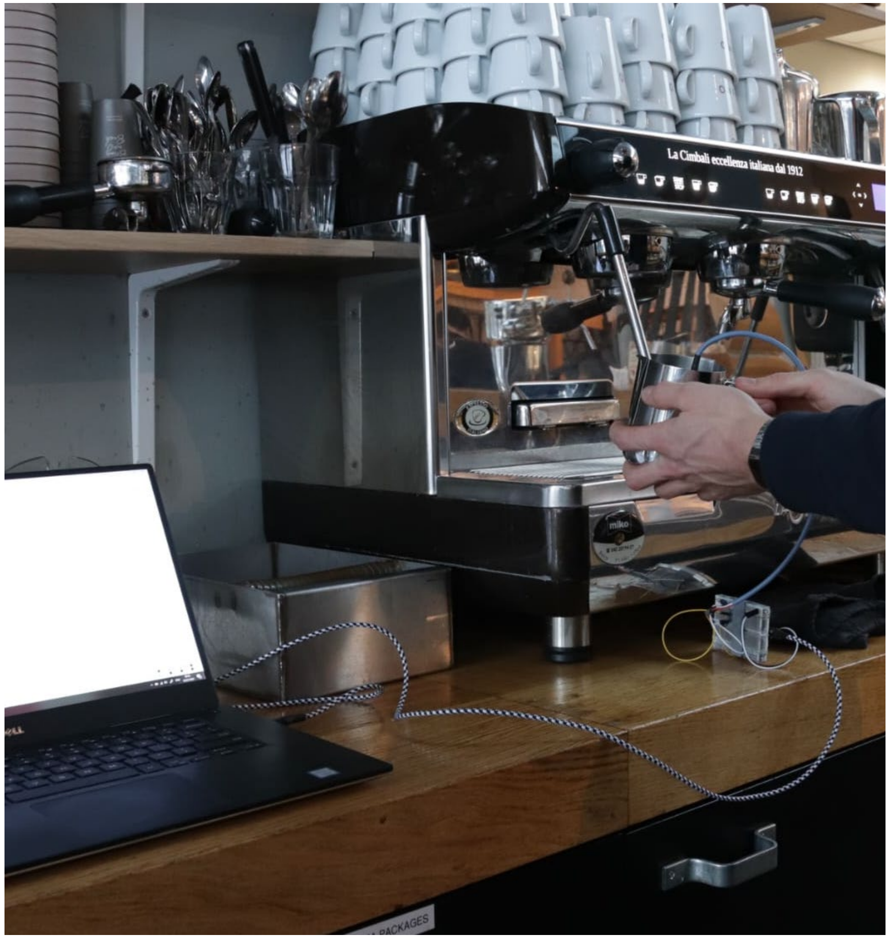


Figure 19: Recording of data in the first part of the café machine evaluation.

In the second phase of the study, the steam wand tip was detached from the steam wand. Subsequently, a test setup was connected to the steam wand, and the detached tip was inserted into this arrangement. Within this setup, a flow meter and temperature probe were installed. Figure 20 shows the performance test being executed.

Figure 20: Recording of data in the second part of the café machine evaluation using the custom made test setup.

3.6.2 Results

The study was conducted in four cafés in Delft, the cafés were identified within the facinity of the Faculty of Industrial Design Engineering and to have different espresso machines. Each café used a different manufacturer and model of espresso machines and one of the machines was brand new. The machines analysed in this study are:

Sanremo Café Racer	La Cimbali M34
LaMarzocco Linea Classic	Wega Pegasus

To explain possible differences in results between the different espresso machines, it is important to have a global view of the properties of each machine. Table 4 shows the comparison of the machine characteristics identified by the theoretical model being of influence on the performance of the system.

Table 4: Machine characteristics of the espresso machines in the study.

	Sanremo Café Racer	LaMarzocco Linea Classic	La Cimbali M34	Wega Pegasus
Nozzle holes (#)	4	4	3	4
Nozzle hole size (mm)	1.3	1.5	1.5	1.5
Nozzle single hole equivalent (mm)	2.6	3.0	2.6	3.0
Power rating (kW)	3.85	4.0	3.75	5.0
Boiler size (L)	10	11	10	17
Boiler pressure (barG)	1.3	1.5	1.3	1.1
Control	PID pressure & PID temperature	PID temperature	Mechanical temperature	Mechanical pressure

Phase 1

The output from the first phase of the research is expected to be graphs similar to Figure 21. In these graphs, the part of interest is the highlighted steep curve, this is the water temperature over time. The test is repeated 3 times and results are averaged.

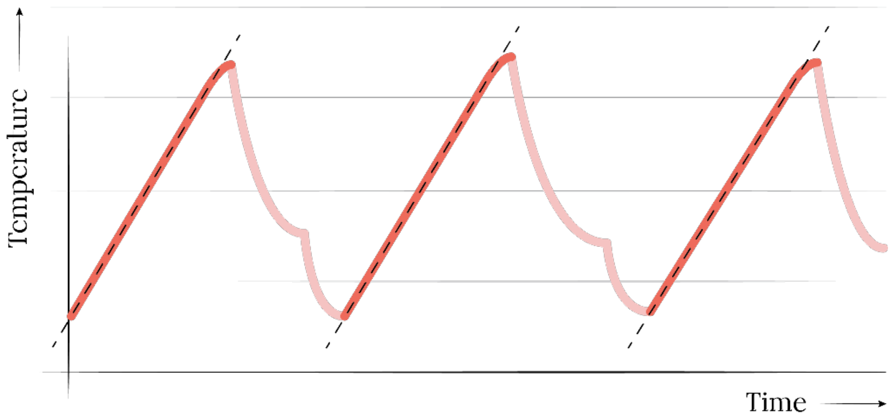


Figure 21: Expected output of the data gathered in this phase

The information we want to extract from data is the heating potential of the system. We can do this by plotting a trend line onto the highlighted part.

The function that describes the trend line, gives the temperature change of the liquid. With this temperature change over time, we can calculate the energy requirement using the function:

$$Q = m * c * \Delta T$$

The boiler efficiency is determined by the function:

$$\eta = \frac{P_{output}}{P_{input}} * 100$$

	Temperature change (°C/sec)	Energy requirement (W)	Boiler efficiency (%)
Sanremo	2.967	2482	64.5
LaMarzocco	2.891	2359	59.0
Wega	3.309	2769	55.4
La Cimbali	2.773	2320	61.9

The Wega espresso machine seems to have exceptionally high steam flow rates, compared to the other machines in this sample. This was also noted during the study, as it was difficult to control the liquid in the pitcher. When looking at the machine characteristics of the machines in this sample, there are two factors that could explain the difference in flow rate between the machines; power rating and boiler size. It is most likely that the factor causing this difference is the power rating of the heating element in the boiler of the Wega machine. The power of the heating element directly determines the amount of steam that can be generated. Combined with the nozzle, it determines the flow profile.

Phase 2

Similar to phase one, the data acquired can be best visualized in graphs. The data collected is volumetric flow rate and steam temperature. By plotting the flow rate data and creating a trendline during the steaming operation, we can determine the average flow rate and flow rate decrease over time. The steam temperature data does not seem to correlate to the values provided by built in sensors on the espresso machines and the theoretical model. Due to the lack of correlation, these datapoints have been excluded from the analysis.

	Average flow rate (L/min)	Flow rate change (L/sec)
Sanremo	14.11	-0.10
LaMarzocco	15.00*	-0.14*
Wega	19.66	-0.10
La Cimbali	14.93	-0.14

* Based on a single measurement

As expected from the results of the first phase of the research, the Wega espresso machine has a significantly higher steam output than the other three machines. Based on the machine characteristics of the other three machines; nozzle single hole equivalent and boiler pressure and heating element power, it is expected that the LaMarzocco would have the highest output, followed by the Sanremo and lastly the La Cimbali. This is not reflected by the results.

The difference between the Sanremo and the La Cimbali machine might be explained in another machine characteristic: the amount of nozzle holes. When steam passes through the nozzle holes, it experiences drag from the walls of these holes. With similar nozzle areas, the nozzle with more holes has a larger total circumference, inducing more drag.

3.6.3 Conclusion

From the tests conducted on several commercial espresso machines, more requirements for the creation of the concept can be drawn up. Furthermore, a realisation has dawned, namely that the introduction of a lot of turbulence might also have a negative side to the user-experience. With increased turbulence, there is an increased chance lose control over the foaming process, ruining the foam quality and possibly cause spillage of milk.

A5	Product must have an average volumetric flow rate of at least 14.52 L/min
A6	The product must be able to heat 200mL of water from 7 to 60 °C in approximately 20 seconds
A11	Product must retain a relatively constant steam flow with maximum average reduction in steam flow of 12%

3.7 Compliance

Product compliance is a critical facet in the design and development of any new product. It involves ensuring that a product meets all regulatory requirements, industry standards in different markets. During the design phase, considering compliance helps to mitigate risks, avoid costly redesigns, and reduce the time to market. In the development stage, it ensures that the final product is safe, reliable, and ready for acceptance in its target market. Different markets have different regulation, for now the main focus is on the European market. This chapter therefore captures all the regulatory requirements for products in the EU and industry standards that apply to a milk frother.

3.7.1 Approach

Your Europe (2024), a website managed by the Directorate General for Internal Market, Industry, Entrepreneurship and SMEs of the European Union (EU), provides a list of steps that help guide manufacturers to create products to be sold in the EU that conform with EU regulations. In this stage of the design and engineering process the following information is required and is therefore provided in this chapter:

1. Identify the requirements that apply to your product, EU-wide and in the country in which you wish to sell it.
2. Check whether harmonised standards exist for your product

The Accss2Markets database is used to find the appropriate rules and regulations. The database is structured around custom codes. Before being able to access the information, the customs code according to the Harmonized System (HS) must be identified.

Identifying the HS customs code applicable to the product to be designed, is done through searches on Zauba, a website logging global import and export data. Searches will be conducted with the terms “frother”, “foamer”, “steamer” stand alone or combined with the keywork “milk”.

3.7.2 Results

Two HS customs codes are identified that could be applicable to a milk steamer as described previously:

1. 85 16 71 – "Coffee machines" – imports with this code included Nespresso Aeroccino
2. 84 19 81 – "Percolators and other appliances for making coffee and other hot drinks"

The two HS-codes describe different types of product, however, after analysing these paths; 85 16 71 – 'Other electrothermic appliances, Coffee or tea makers' and 84 19 81 - 'Other machinery, plant and equipment, For making hot drinks or for cooking or heating food', both HS-codes could still apply for to a milk steamer.

Finally, the requirements for the two identified HS-codes for our product were compared. This comparison revealed that the HS-code have just one difference in their respective requirements regarding the maximum power consumption during standby and off modes of the products. Since the requirements are rather similar, to be sure, compliance will be sought for the most strict HS-code: 85 16 71.

The requirements from this analysis include: food safe materials, quality control standards, RoHS compliance, electromagnetic compatibility, safety standards and ecodesign. These requirements already include the harmonised standards that the product must adhere to such as: Machinery (MD) and Low voltage (LVD).

3.7.3 Conclusion

G1	Product must adhere to Regulation (EC) 1935/2004
G2	Product must adhere to Regulation (EU) 2022/1616
G3	Product must adhere to Regulation (EU) 10/2011
G4	Product must adhere to Directive 2012/19/EU
G5	Product must adhere to Directive 2014/30/EU Electromagnetic Compatibility (EMC)
G6	Product must adhere to Directive 2014/35/EU
G7	Product must adhere to Directive 2006/42/EC

List of Requirements

In this chapter, the list of requirements is stated. This list determines all the requirements the concept to be developed should meet

All requirements of the research stated previously can be combined into a comprehensive list of requirements (Appendix VII) that must be referenced to in the design and development stages of the prototypes. Since the goal of this project is to develop a prototype of a milk steamer that has similar or even improved steaming performance as commercial espresso machines and create perfect milk foam, only requirements regarding this performance will be referenced during this project. Other requirements gathered during this project should be satisfied somewhere in the development phase of the concept, however for the purpose of this project they will be left out. The list of requirements regarding the performance of the product are noted in the table below.

Category	#	Wish or requirement	Description
A Performance			*What main functions does the product need to fulfil?* *What functional properties should it have (speed, power, strength, precision, capacity, etcetera)?*
	1	Requirement	Product must be able to create foams with maximum bubble size of 200μm using all types of (alternative) milk
	2	Wish	Product should create foams with as uniform bubble size spread as possible
	3	Requirement	Product must give user full control over the foaming process
	4	Requirement	Product must be able to foam two drinks before the need for refilling/getting up to temperature
	5	Requirement	Product must have an average volumetric flow rate of at least 14.52 L/min
	6	Requirement	The product must be able to heat 200mL of water from 7 to 60 °C in approximately 20 seconds
	7	Wish	Product should be ready for foaming as fast as possible.
	8	Wish	Product should require as few steps as possible to be cleaned
	9	Wish	Product should feature a piggyback wall plug
	10	Requirement	Product must be able to increase the volume of all types of (alternative) milk by 50% through foaming.
	11	Requirement	Product must retain a relatively constant steam flow with maximum average reduction in steam flow of 12%
	12	Requirement	Product must not dilute the milk with water by more than 15%
	13	Wish	Dilution of the fluid to be frothed should be as low as possible.

	14	Requirement	Product may not cause electromagnetic disturbance exceeding the level above which radio and telecommunications equipment or other equipment cannot operate as intended,
	15	Requirement	Product must have the adequate level of immunity to such disturbance which allows them to operate without unacceptable degradation of their intended use.
B Environment			*What kind of environmental influences does the product need to withstand during production, transport and use (temperature, vibrations, moisture, etcetera)?* *What effects of the product to the environment should be avoided?*
	1	Requirement	Parts must withstand temperatures above 100 °C
	2	Requirement	Parts must withstand humid environments.
	3	Requirement	Product must withstand splashes of water for short duration
	4	Requirement	Product may not give off to other surfaces due to heat or humidity
C Maintenance			*Is maintenance necessary and possible?* *What parts need to be accessible?*
	1	Wish	Product must consist out of as many off the shelve components as possible.
D Target product cost			*What is a realistic price for the product, considering similar products?* *What margin does it need to deliver?*
	1	Requirement	Product may not cost more than €300 to customers
E Size and weight			*Are there boundaries to the size and weight of the product due to production, transport or use?*
	1	Wish	Product should require as little counter space as possible
F Materials			*Should certain materials (not) be used (because of safety or environmental reasons)?*
	1	Requirement	Materials used to construct the product must not bring about deterioration in the organoleptic characteristics

G **Standards, rules and regulations**			*What standards, rules and regulations (nationally and internationally) apply to the product and to the production process?* *Should standardisation within the company or with the industry be taken into account?*
	1	Requirement	Regulation (EC) 1935/2004
	2	Requirement	Regulation (EU) 2022/1616
	3	Requirement	Regulation (EU) 10/2011
	4	Requirement	Directive 2012/19/EU
	5	Requirement	Directive 2014/30/EU Electromagnetic Compatibility (EMC)
	6	Requirement	Directive 2014/35/EU
	7	Requirement	Directive 2006/42/EC
H **Safety**			*Should specific precautions be taken with regard to the safety of users and non-users?*
	1	Requirement	Product does not endanger persons, domestic animals and property in foreseeable conditions of overload.
	2	Requirement	Product must have fail-safes to prevent a heating element explosion.
	3	Requirement	Product must have sensors to prevent product self-damage.
	4	Requirement	Persons and domestic animals are adequately protected against the danger of physical injury or other harm which might be caused by direct or indirect contact;
	5	Requirement	Temperatures, arcs or radiation which would cause a danger, are not produced;
	6	Requirement	Persons, domestic animals and property are adequately protected against non-electrical dangers caused by the electrical equipment which are revealed by experience;
	7	Requirement	Product must protect against any risk caused by the use of machinery (mechanical risks, electrical risks, extreme temperatures, fire, explosion, noise, radiation, emission of gases, risk of being trapped in a machine, etc.).

04.

Develop

This chapter describes the process designing, testing and evaluating a proof of concept prototypes. These prototypes are designed based on the system previously modelled and the list of requirements, technologies are identified and practically compared with the goal of selecting the components for the final design.

4.1 Design focus

The goal of this quadrant is to develop and evaluate concept prototypes. From the café machine evaluation, we have identified that the nozzle combined with the heating element almost exclusively determine the flow profile of the system. The heating element dictates the amount and temperature of the steam that can be generated while the addition of a nozzle determines the mass flow rate and the velocity of the steam. Due to their importance, these two components will therefore be prioritized during the development.

The identification and selection of other other components will be selected based on their impact on user experience, price and possible (negative) implications on the functioning of the product.

Part selection for the prototypes generally follows these steps in chronological order:

1. Calculate and define operational parameters
2. Literature review to identify potential parts
3. Assess the availability and cost of the options
4. Compare and select promising technologies
5. Build prototypes to evaluate the parts

4.2 Heating element selection

In this concept, steam plays a two-fold role. It serves to heat the milk and simultaneously generates internal forces, leading to turbulence. This turbulence is crucial in capturing air within the milk and reducing the size of the bubbles. Generally, we can state that when the pressure generated by the heating element is higher, the higher the flow rate when opening the release valve. The maximum steam that can be created by the heating element is directly proportional to the power of the element.

4.2.1 Operational parameters

For the identification of the right components it is important to calculate and define operational parameters. Important aspects of the concept, determined by the heating element are the start-up time and the dryness of the foam that can be achieved. From the list of requirements we can also retrieve important decision criteria:

During the selection process of heating elements, it is important to keep the list of requirements in mind. The applicable requirements from that list are stated below.

A4	Product must be able to foam two drinks before the need for refilling/getting up to temperature
A6	The product must be able to heat 200mL of water from 7 to 60 °C in approximately 20 seconds
A7	Product should be ready for foaming as fast as possible.
A11	Product must retain a relatively constant steam flow with maximum average reduction in steam flow of 12%
A12	Product must not dilute the milk with water by more than 15%
D1	Product may not cost more than €300 to customers
E1	Product should require as little counter space as possible

4.2.2 Technology identification

During the examining current espresso machines on the market, a variety of technologies for steam generation are observed, including boilers, thermocoils, thermoblocks, and thick film heating elements. Next to this, more information on the applications of different types of heating elements was gathered from other sources. Hegboom (1997) describes heating elements often found in domestic appliances. The elements mentioned in the chapters “Heating of Water and Beverages” and “Drying and Ironing” were gathered identifying whether they could create steam. The elements included in the analysis were: tubular heaters, open coils, embedded tube heaters, sheathed mica and PTC.

With this information in mind, the elements could be evaluated for their functionality in the application of a milk steamer and component availability. Out of all the heating elements, three were selected for their very different modes of operation: boilers (tubular heaters) and flow through heating elements in the form of thermocoils and thick film heating elements.

Notably, these technologies are already prevalent in existing espresso machines. Thermoblocks, although similar in performance to thermocoils, are not selected due to their negative perception within the coffee community, particularly concerning their tendency to leak. Cast-in heating elements and thick film heating elements are considered as flow through heaters having similar modes of operation.

4.3 Integrated prototypes

The prototypes created in this stage of the project are to learn the influence of specific components, such heating elements on the overall performance of the concept. With the prototypes hypotheses about nozzle geometries can be tested. Based on the results of the tests at the end of this phase, a heating technology is selected based on the list of requirements.

The development of prototypes is subdivided in several stages, starting with the definition (supportive) components based on the heating technologies, followed by the design of the system architecture, creation of the supporting computer code and ending with the assembly and testing of the prototypes.

In this stage of the project, 5 different heating elements must be evaluated (2 boilers, 2 thick film elements and 1 thermocoil). Building 5 prototypes would require to much time, therefore the prototypes were constructed to facilitate easy modification and the carry-over of many components. The prototypes are constructed on 4040 aluminium profiles, allowing for on the fly adjustments and easy repositioning of components. The two flow through elements require roughly the same components, due to their similar modes of operation. This also allowed the swapping of these different types of heating elements, requiring the construction of just two frames.

In the design of the supportive frames, several design considerations were taken into account. Firstly, the steam wand was positioned at a higher level to accommodate pitchers of various sizes beneath it. Although a platform can be introduced to reduce the space under the steam wand, expanding the space later proves to be a greater challenge. Additionally, a partition was incorporated to separate the steam area from the electronic components, effectively safeguarding the electronics from steam exposure and as a location for mounting the different heating elements.

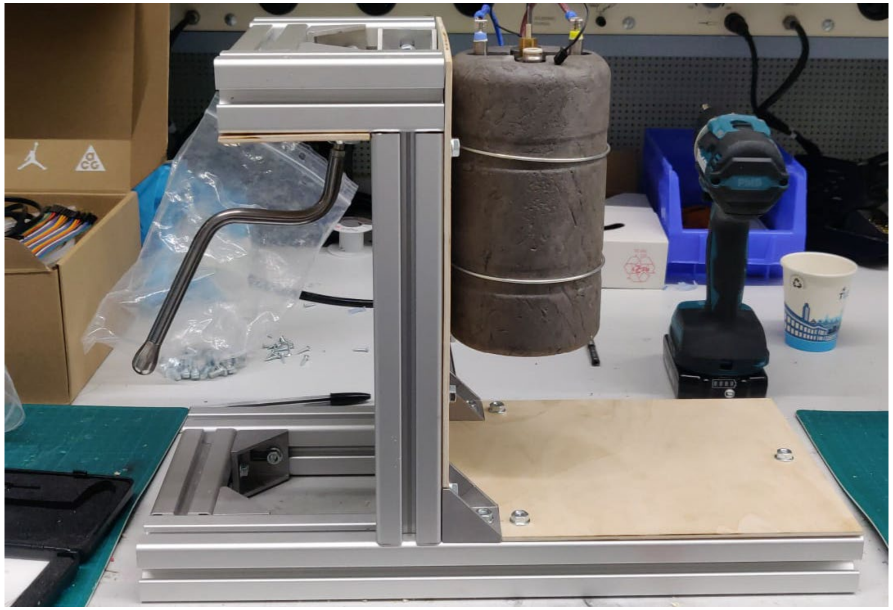


Figure 22: Almost empty support frame for the integrated prototypes

4.3.1 Safety

There are safety hazards associated with the prototypes that are being developed such as exposure to high voltage and the use of pressure vessels. As it is of utmost importance to guarantee the safety of every person interacting with the prototypes, safety protocols and components must be implemented. Safety is also an important part of showing compliance with the EU regulations, as reflected upon in chapter 3.5. This chapter discusses all safety measures implemented during the prototyping phase of the project.

The risk associated with high voltage is addressed through three distinct mechanisms designed to halt the prototypes' operations electronically at any stage of their evaluation:

1. Disconnecting the prototype's power cord from the electrical outlet, cutting all high voltage.
2. Engaging the external on/off switch located on the prototype's electronics compartment, cutting all high voltage.
3. Severing the power supply to the Arduino by detaching the USB cable, closing all valves and halting all electrical components.

Additionally, all terminals handling 230V are shielded as much as possible using heat shrink, to minimize chance of exposure. The electronics compartment is closed off as much as possible, while still allowing for the passage of cables, which serves to minimize the risk of accidental contact with active electronic components and provides a measure of protection against any liquid or vapor spills.

Creating steam requires the building up of pressure. All heating elements are rated for a maximum amount of pressure, but it is not recommended to approach those pressures. To safeguard against the risks of physical injury or damage to components, a safety valve calibrated to release at the pressure of 3 barG has been installed on each prototype. This valve is designed to open and relieve pressure if it surpasses 3 barG within the heating element, thereby preventing excessive pressure buildup.

All heating elements have pre-installed mechanical thermostats to cut-off the power to the heating element when it exceeds various temperatures (150 °C for thermocoil, 160 °C for boiler and 318 °C for the thick film heating element. This ensures that the power to the heating element is cut before the element is damaged or causes a safety hazard to the user of the prototype/product.

4.3.2 Boiler prototype

Boilers, commonly used in commercial espresso machines, present a compelling option for consideration. These machines typically feature large boilers, about 10 liters in size, which provide excellent performance. However, such a large volume is not suitable for the concept due to space requirements, heating time, and power consumption. Furthermore, as stated in chapter 4.5.2, the intensity of steaming is highly dependent on the capacity of the boiler built into the machine, it is important to test multiple boiler capacities.

A European supplier offering compact, high-quality boilers was identified, with sizes ranging from 500-800 mL and power outputs of 1500-2500W. To best determine the influence of boiler size on steaming performance, the smallest and largest boilers available (Figure 23), both equipped with 2000W heating elements are selected for analysis.

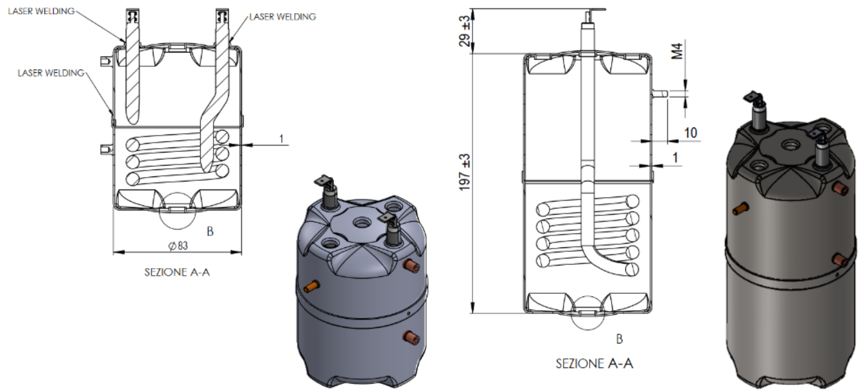


Figure 23: Different boiler formats identified for testing.

The manufacturer delivered the boilers mostly assembled, the following parts are selected by the boiler manufacturer; safety thermostat, heating element, push-in fittings, NTC and water level probe. The boiler also comes with detachable insulation that is specially designed to fit that specific boiler. As mentioned previously a over-pressure valve is added to the boiler and an additional safety component that was selected for this heating technology is a anti-vacuum valve. This valve is open when the pressure inside the boiler equals the atmospheric pressure, allowing air inside the boiler to escape during heat-up of the boiler allowing the boiler to fill with steam.

Due to the heating technology used, systems with boilers are unable to create superheated steam, due the abundance of water in the boiler vessel. When steam passes through the surface of the water, it will carry a small amount of water with it, resulting in unsaturated steam. This means that special attention must be paid to the adsorption of water into the milk of these prototypes.

System architecture

Many espresso machines use boilers as their source of heat. Therefore, determining the supporting components was done by looking at the spare part lists of commercial espresso machines.

There are some notable differences for this boiler compared to espresso machines. Espresso is prepared at very high pressures (usually 9 barG), which requires a pump that can provide this pressure. The maximum pressure of this system is determined by the safety valve. The safety valve is rated for 3.0 bar, therefore the maximum pressure the pump must be capable of producing is 3.0 barG. For this stage of development, a pump that was already in our inventory was used in the prototype.

The switches used to provide power to the heating element within the boiler and the solenoid valve are both electromechanical relays, because there is no need for fast switching and these relays are very affordable. In later stages of development, it should be determined how long the product could last using a mechanical relay based on the expected cycles per use of the machine. The entire system architecture is depicted in Figure 24.

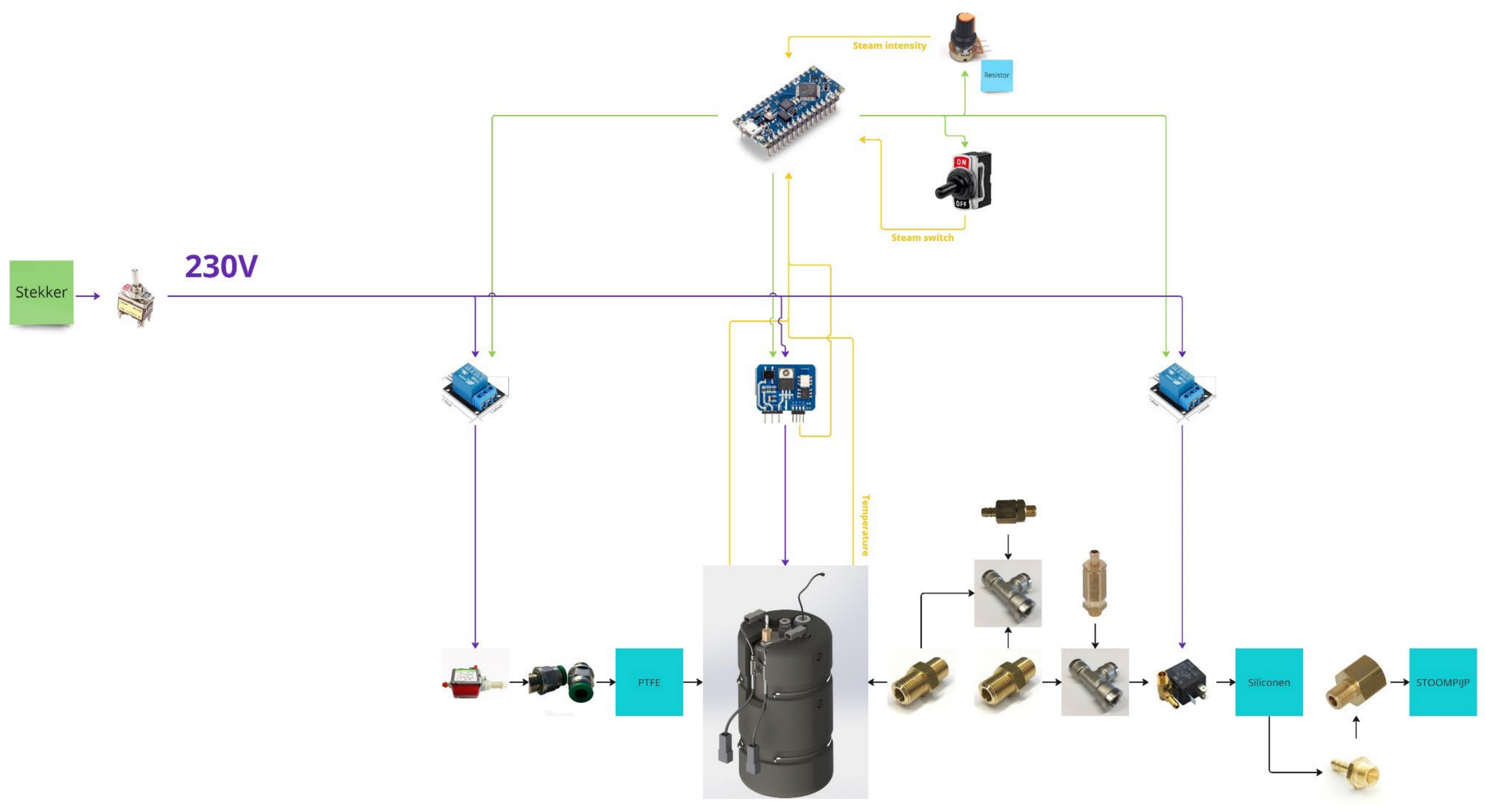


Figure 24: System architecture of the boiler prototype.

4.3.3 Flow through heating elements

Both the thick-film heating and thermocoil heating elements function in a similar way, they immediately heat water that is pumped through the elements. For these elements it is important to supply a predetermined amount of water to the element. To do so, pumps must be modulated supply the required flow rate. To determine what pumps are most suitable for this application, research into pumps was conducted.

Pump selection

According to The Engineering ToolBox (2003), there are two classifications of pumps; centrifugal and positive displacement pumps. Positive displacement pumps are more suitable than centrifugal pump for this application, because they offer constant flow regardless of the system pressure and they generally generate more pressure than centrifugal pumps.

GlobalSpec was identified as a supplier/distributor look-up website. On this website it is possible to search product categories for proper part selection and distributor networks for these specific parts.

By searching the category 'miniature positive displacement pumps' and 'micro positive displacement pumps', the following possibilities for positive displacement pumps for this application are identified:

Diaphragm pumps	Piston pumps
Peristaltic pumps	Gear pumps

Of this selection, rotary pumps are in theory more interesting, because they have a constant delivery of fluid, whereas reciprocating pumps have a pulsating flow. In the application of flow through heating elements this might mean that it is easier to modulate the heating element, because it has a constant flow of 'cold' water, instead of small batches of cold water. Furthermore, a more constant flow of water would also mean that the delivery of steam is also more constant.

In the end, two gear pumps were identified through Alibaba. These pumps were ordered and in the meantime, the same ULKA piston pump was used to carry out prototype tests. Two different methods of pump modulation were tested (Figure 25): Pulse Skipping Modulation (PSM) and using a needle valve to reduce flow.

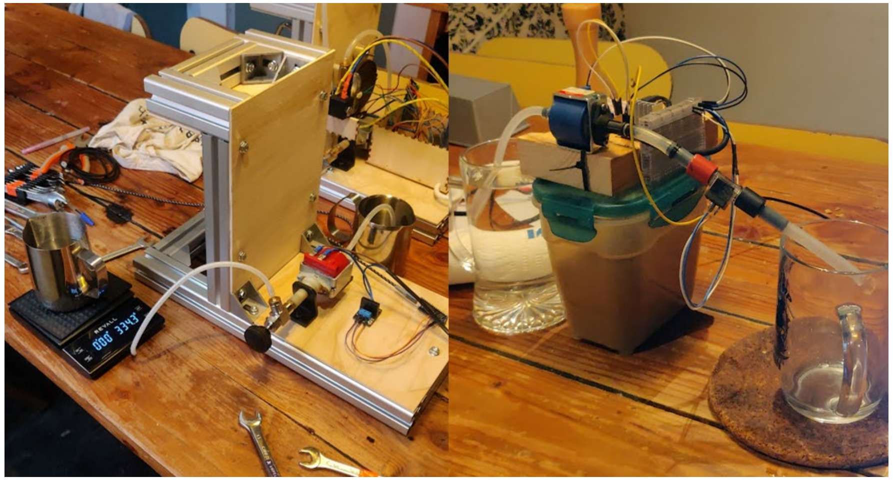


Figure 25: Flow modulation testing using reciprocating piston pumps.

It was very difficult to modulate the flow of the pump using just the needle valve. Using PSM, it was possible to get within a percentage points of the required flow rate. Since this requires switching the pump very quickly, the power is provided by a solid state relay (SSR).

The two heating elements must be controlled differently, to adhere to the Directive 2014/30/EU Electromagnetic Compatibility (EMC). Ferro Techniek, the manufacturer of the thick-film heating elements has evaluated how to meet these regulations. They suggest using a control method called Pulse Skipping Modulation (PSM). The best way to modulate the thick-film heating element to meet the regulations is by implementing a PID with a long sample time and switch the heating element on/off during a zero-cross to reduce the introduction of noise.

Thermocoil

A thermocoil consists of a tubular heating element and fluid tubes that are coiled in close proximity of each other and then cast in aluminium. Preferably the power of this heating element is the same as the boilers previously described, however there was no thermocoil available with 2000W of power, resulting in the selection of the next best thing. This thermocoil uses 1900W of power. The tubular heating element does not come in contact with the water to be evaporated and relies on conduction through the aluminium to heat the water to the required temperature. Thermocoils are considered to be very temperature consistent due to their thermal mass.

Theoretically it would be possible to create superheated steam using this method, however in our testing this was not achieved. Contributing factors to this are relatively large tube diameter and the element power rating and the fact that is supplies heat indirectly. Creating super heated steam with this element would require extremely slow pumping speeds, which would reduce the maximum amount of steam that can be created.

An approximated of the heat losses of such an element due to convection are around 40W. This is only a fraction of the power rating, therefore these losses can be neglected when calculating the maximum amount of steam that can be produced.

The maximum amount of water that can be turned into steam with this element can be calculated using the following equation:

$$P = m_{water} * C_{vaporization} + m_{water} * C_{p,water} * \Delta T_{water}$$

Assuming there are no losses, the maximum amount of water that can be turned into fully dry steam with of 130°C, is 0.72mL/sec or 43.3 g/min.

Thick-film heating element

Thick film heating elements have the lowest thermal mass of all three technologies, while still having a power rating of 1300 and 1800W. This means that the temperature gradient of the element is very steep and start-up time is in the region of seconds. The heating elements, FTH MKII, in this project are kindly provided by Ferro Techniek. The elements are already used in espresso machines by Sage/Breville as and in the two stand-alone milk steamers that have recently launched on Kickstarter which, for home machines offer decent steam flow.

These elements are constructed with two heating tracks, a low power track and a high power track. To make use of the full power of the heating element, two SSR's are required. The other prototypes have a single heating element, requiring just one SSR. Making use of PSM and having two separate heating elements allows for more precise temperature control. The FTH MKII has 24 heating states compared to the 2 states (on and off) of the boiler and thermocoil.

Using the same equation as the thermocoil, the maximum amount of liquid that can be turned into 130C steam under ideal conditions is 41.3 mL/min for the large element. If, at full power of the heating element, the flow of the pump is reduced, superheated steam is expected to be formed in the element.

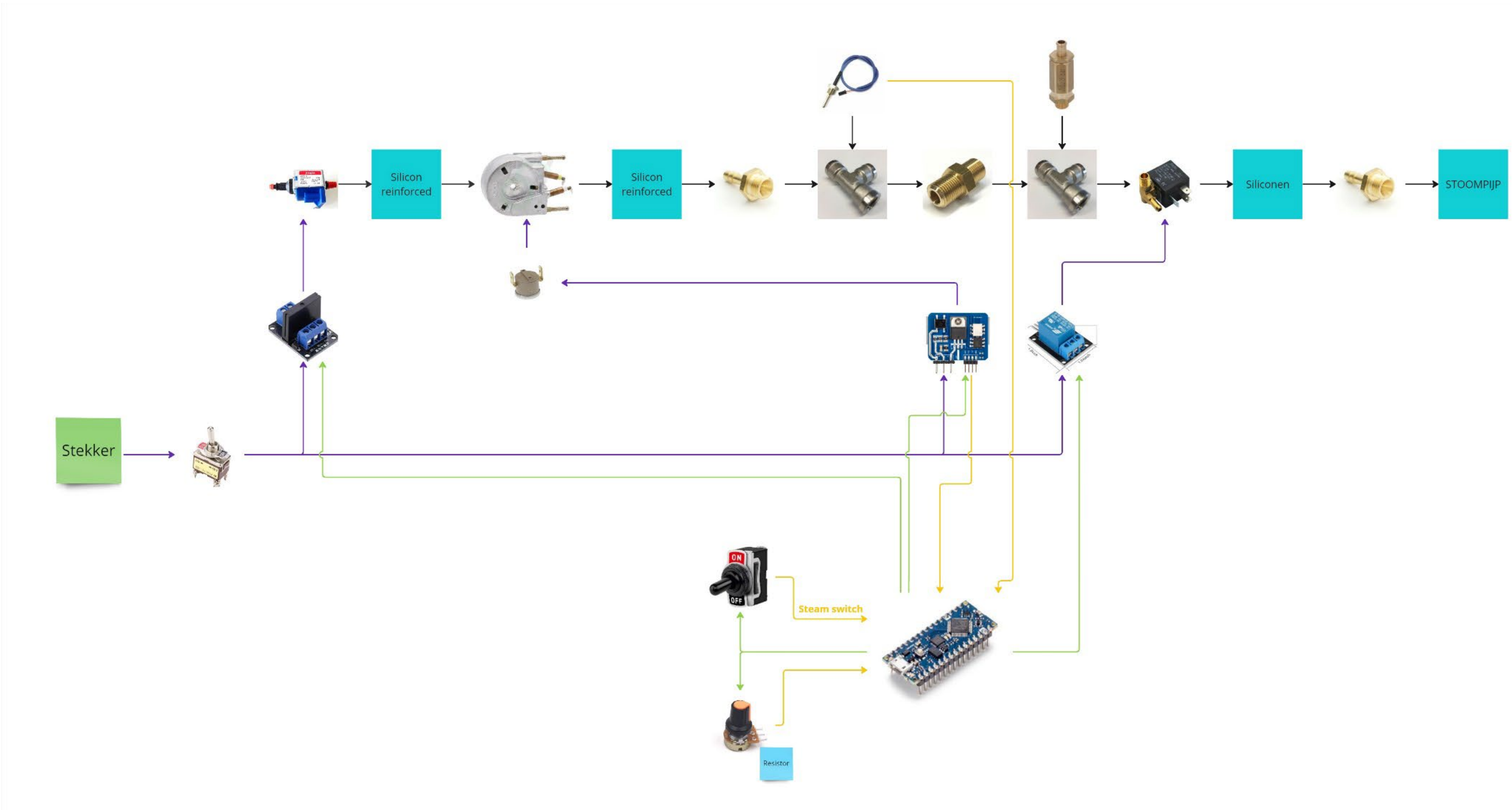


Figure 26: System architecture of the thermocoil heating element.

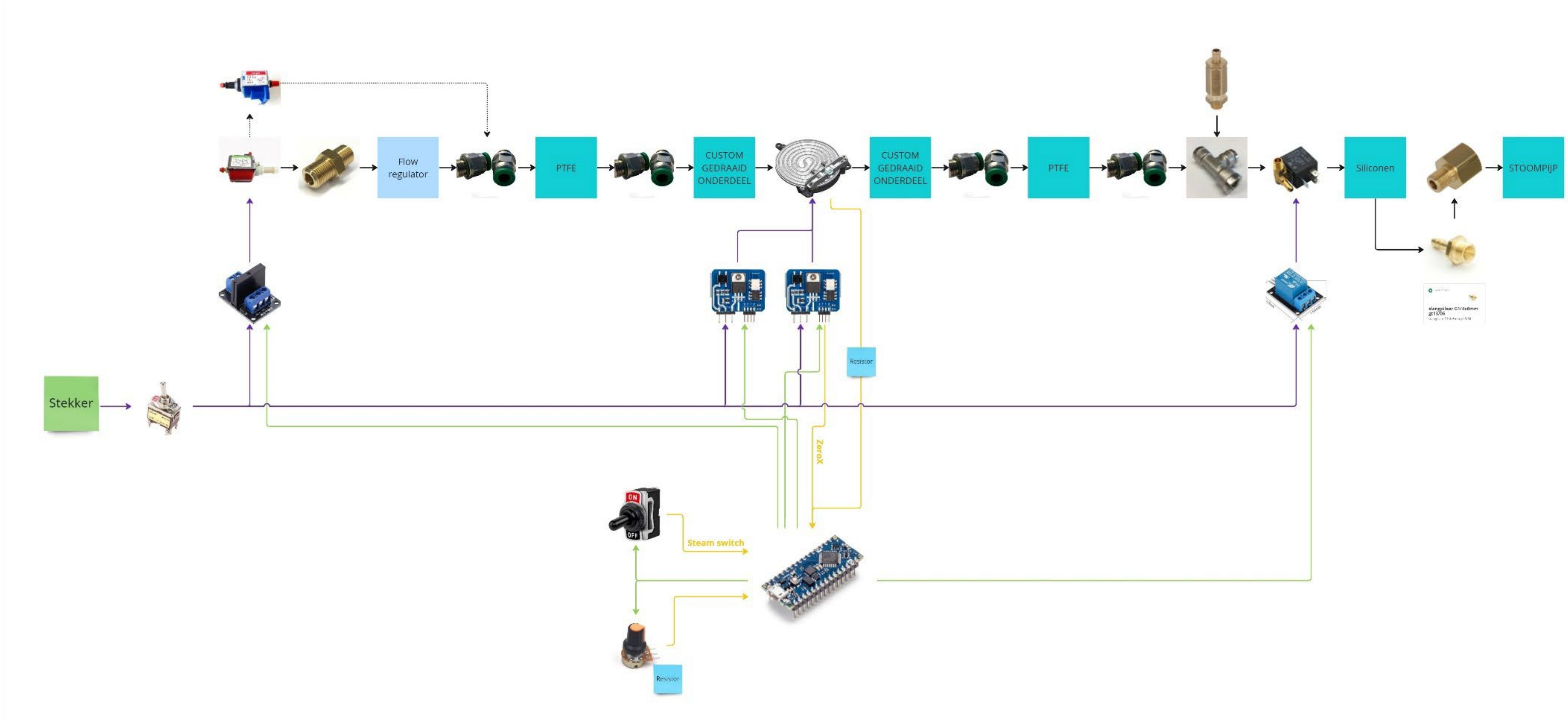


Figure 27: System architecture of the thick-film heating elements.

4.3.4 Building the prototypes

The prototypes were mostly constructed in the PMB workplace in the Faculty of Industrial Design Engineering. All of the heating elements were mounted to the wooden panel separating the steaming side of the prototypes from the hardware and electronics side. The mains voltage components such as the solid state relays, switches and mechanical relays were placed within the wooden boxes in Figure 28.

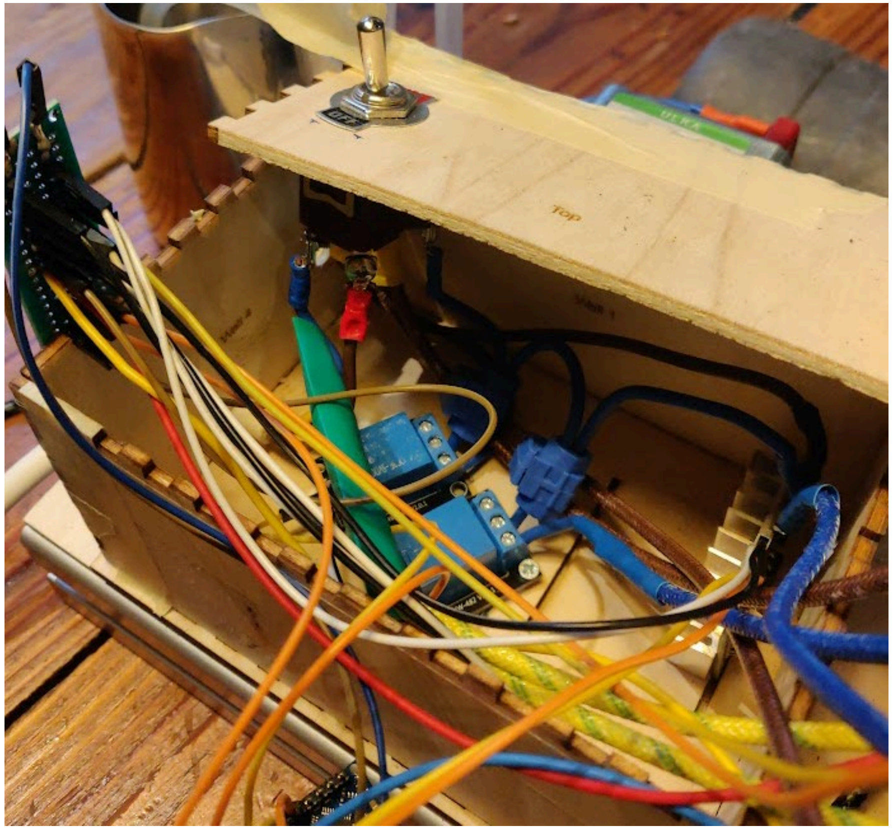


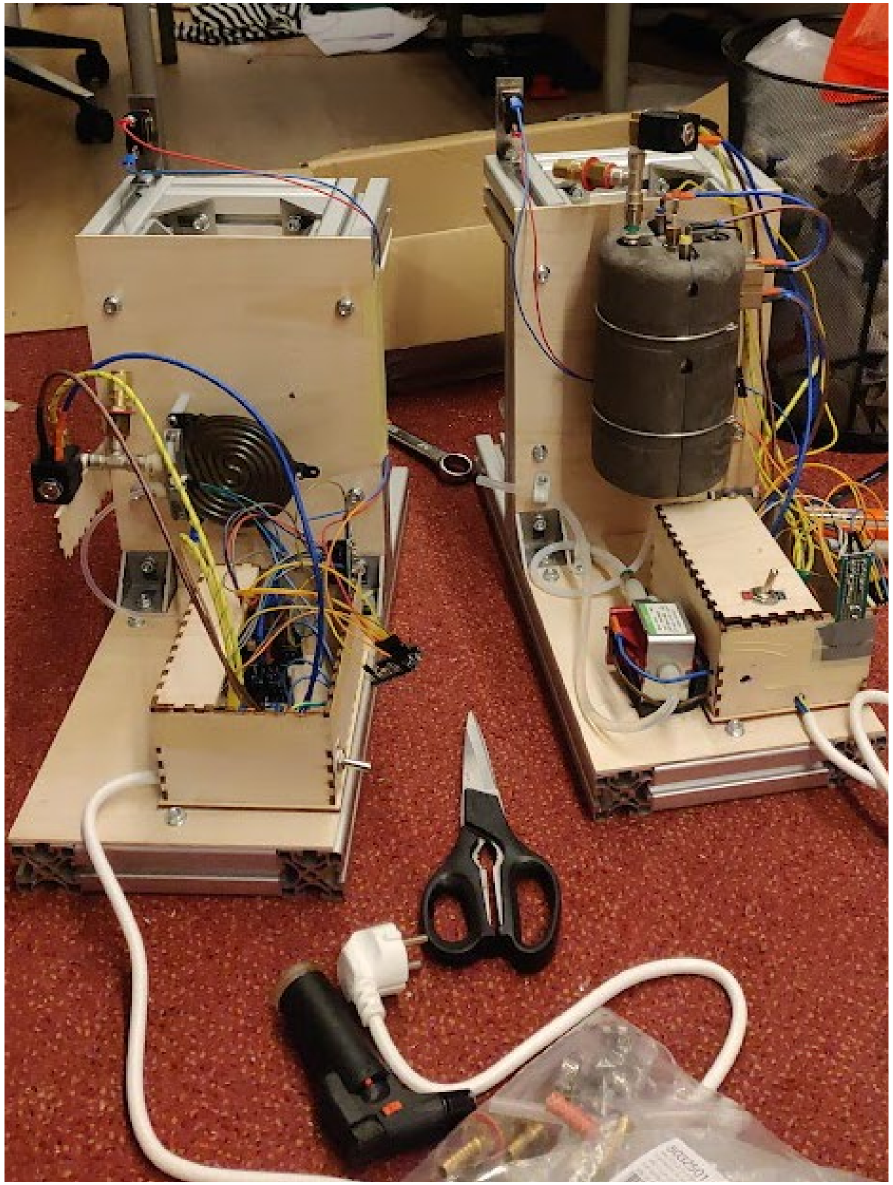
Figure 28: Box shielding the mains voltage components.

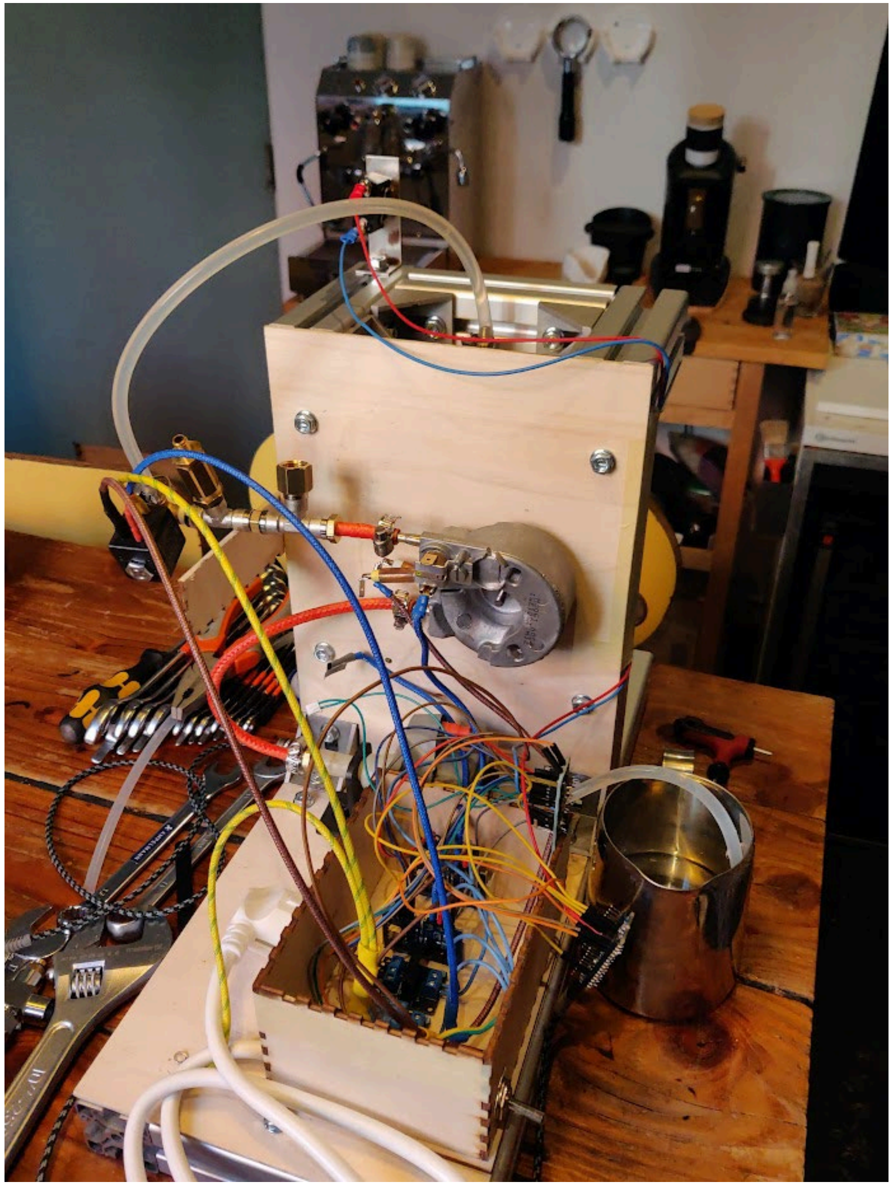
Furthermore, all mains voltage wires that were located close to parts that can get hot because of contact with steam – heating elements and solenoid valves – are made out of glass and silicon which shields the wire from heat.

There were a few parts that needed modification to properly fit and a new component had to be created (Figure 29). This adapter allowed attaching a push-in connector to the thick-film heating element.

Figure 29: Adapter for the thick-film heating element.

Slowly the prototypes started to take shape. There is no picture of all the prototypes in one image, because there were only two frames built as mentioned previously. The final prototypes for each of the heating elements are displayed on the following page.





4.4 Prototype evaluation

The integrated prototypes serve to provide information regarding the performance of different sub-systems and technologies implemented in these prototypes. Based on the list of requirements, the following data should be gathered during the evaluation of the prototypes:

- Flow rate profile
- Steam dryness
- System start-up time
- Fluid heat-up capabilities
- Pump speed (only for flow through element)

4.4.1 Study design

The evaluation of the prototypes created in this phase of the design process is similar to the study conducted on commercial espresso machines. However, there are more phases added to this study. When flow profile is mentioned, the same method as phase 2 of the commercial espresso machine analysis is applied. Altogether, the study of evaluation of the prototypes consists of the following 6 phases:

Phase 1 identifies the influence on nozzle geometry on the flow profile of the system. Commercial espresso machines often feature multiple holes on the nozzle, while entry-level feature just one hole. Furthermore, the results of the second phase of the commercial espresso machine study described in paragraph 3.6 featured a hypothesis on the influence of nozzle design. “With similar cross sectional area, the nozzle with more holes will have a lower flow rate due to increased drag.” To test this hypothesis, a comparison in flow rate was made between a single hole nozzle with diameter of 3mm, followed by a 4 hole nozzle with hole diameter of 1.5mm (Figure . Both nozzles have the same cross sectional area. This test was only conducted on the 800mL boiler prototype.

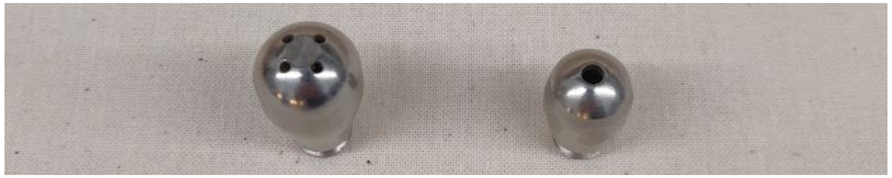


Figure 30: Nozzles used in the first phase of the study

Phase 2 aims to identify the influence of increased cross sectional area on the flow profile of each of the prototypes. Four, single hole, nozzles with increasing cross sectional area were created (Figure 31). The nozzle diameters increased from 1.5mm in increments of 0.5mm.

Figure 31: Nozzles used in the second phase of the study

Phase 3 aims to identify the start-up time of each of the prototypes. All prototypes were heated from room temperature (a sensor reading of approximately 20C) to standby/steaming temperature. The standby temperature for the boilers and thermocoil was set at 120 °C (1.0 barG). The thick-film heating elements do not require a standby temperature due to the extremely high temperature gradient that can be achieved.

Phase 4 is designed to provide information about the fluid heating capabilities and the dryness of steam for each of the prototypes. The method of testing is the same as the method introduced in phase 1 of the commercial espresso machine analysis. The test is performing using all prototypes except the cast-in heater as the NTC used to measure the temperature of the liquid is the same sensor that is needed for the cast-in prototype to function.

Phase 5 studies the influence of pump speed on the performance of the flow through heating elements. The data recorded in this phase is the flow profile that can be achieved. The pump speed is modulated as described in paragraph 4.3.3, starting at 30ml/min and increased in increments of 20ml/min. Another datapoint for a flowrate of 40ml/min can be added, as this flowrate is used in the other phases of the analysis.

Phase 6 aims to visually analyse the turbulence introduced different nozzles in a see-through dosing cup similar to a milk frothing pitcher. The dosing cup and the nozzle are positioned using a guide to ensure that he nozzle is at the same location in the cup, 5mm below the surface of the liquid (Figure 32) for each of the tests. The nozzle is positioned at a location in the cup identified by barista training videos as the perfect location. The cup was filled with 200mL water and a tiny drop of dish soap to emulate the foaming of milk.

Figure 32: Consistent placement of steaming nozzle and dosing cup.

4.4.2 Results

Phase 1

The difference in flow rate between two nozzles of equal cross sectional area, but with different amount of holes has been determined and depicted in Figure 33.

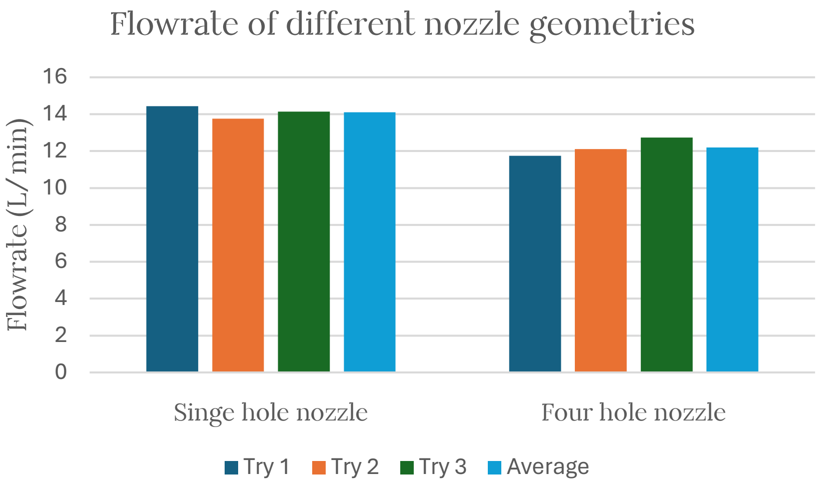


Figure 33: Results of the first phase of the study, displaying flowrates for different nozzles

The average flow rate between nozzles is different by 13.5%, a reduction of that percentage was seen in the nozzle with more holes compared to the single hole nozzle. Although the start temperature of both tests is very similar (within 1 degree). The results from this test seem to prove that my hypothesis described earlier is true. Another interesting insight is that the single hole nozzle adds slightly less water per minute (68.6 g/min) to the drink compared to the four hole nozzle (70.7 g/min).

Phase 2

Comparing the data gathered from the nozzle area increase. All prototypes show an increase in flow rate with an increase of nozzle size (Figure 34).

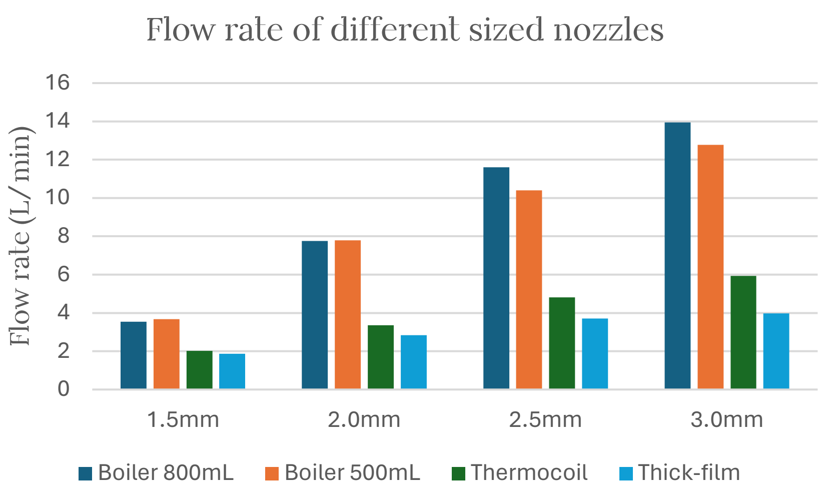


Figure 34: Results of the second phase, showing flowrates for different nozzle areas

From these results we can clearly conclude that the boilers offer a significantly higher flow rate than the flow through heating elements. It is unexpected that the thick-film heating element has the lowest flow rate, as the technology is similar to the thermocoil heater, it was expected to perform similarly. The flow rates of the boilers come close to the performance of the machines studied in the café machine study. These are promising results for further development of the concept.

Interestingly, when looking at the flow rate profiles of the boilers and cast-in heating elements we see an opposite graph. Boilers show a decreasing flow rate over time while the flowrate of the flow through elements increases over time (Figure 35). The increasing flow rate of the thermocoil could give the user more control over the steaming process, especially the aeration stage.

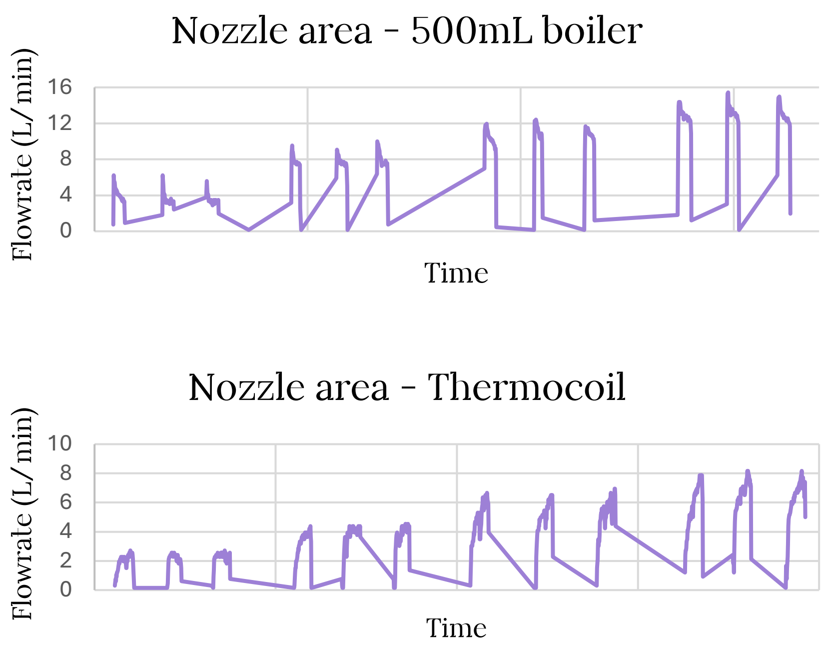


Figure 35: Comparison of flow profiles of boiler (top) and thermocoil (bottom)

Phase 3

The start-up time of the different prototypes was determined in this phase of the research (Table 5). It is expected that the boilers take the longest to reach temperature as a lot of energy is required to heat the water within the boilers. The start-up time of the flow through elements is determined by the thermal mass of the element. Thus, the thermocoil should have a longer start-up time than the thick-film heating element.

Table 5: Heat up times of different heating elements

Heating.technology	Start temperature (C)	Start-up time (s)
Boiler, 800mL	20.3	233
Boiler, 500mL	20.1	135
Thermocoil	20.1	43
Thick-film	20.2	0*

* The start-up time of the thick-film element is 0, because it does not have a standby temperature. However, it takes about 8 seconds to go to full power when steaming with the 1.5mm diameter nozzle.

As expected, the boilers take the longest to heat-up, followed by the thermocoil while the thick-film has no heating time. The heating time of the boilers is not extremely long -at most just under 4 minutes- however as stated before: shorter is better.

Phase 4

The heating capacity of the three different heating elements is compared in this phase of the study. The results are depicted in Figure 36. Based on the results of phase 2 of this study, it is expected that the boiler elements perform rather similarly, while the thick-film element will generate a significantly lower temperature change.

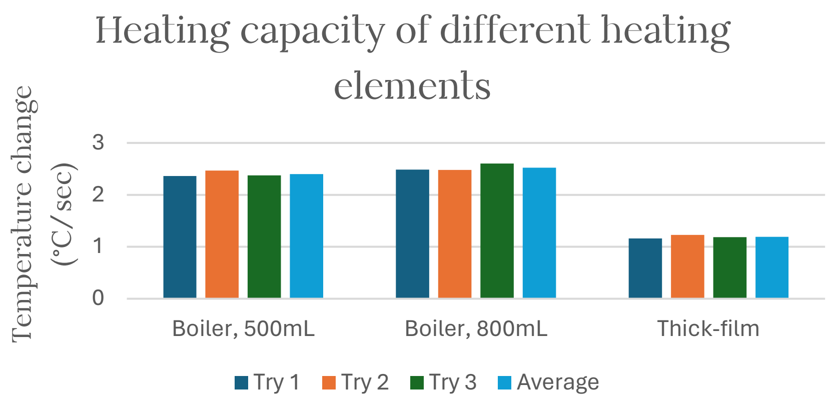


Figure 36: heating capacity of different heating elements

From the results we can conclude that the boiler elements heat the fluid significantly faster than the thick-film element. The boiler elements show very similar performance, with slightly higher heating capacity of the 800mL boiler. The energy required to achieve this temperature change was calculated and showed that this energy is higher the power rating of the elements. This highlights an advantage of boilers over flow through heating elements, during start-up heat energy is stored in the water in the boiler. Later, when the steaming starts, all power of the heating element can go into the phase change from water to gas.

Phase 5

The results of the pump speed on the performance of the thermocoil heating element is depicted in Figure 37. From these results we can see a drop-off of steam flow rate at 70mL/min. At that point, the heating element cannot deliver enough power to heat all the water to steam. Pump flow rates of 30 and 50mL showed similar results, with slightly lower flow rates than 41mL/min recorded in phase 2. The flowrate of 41mL/min was determined as optimal in paragraph 4.3.3.

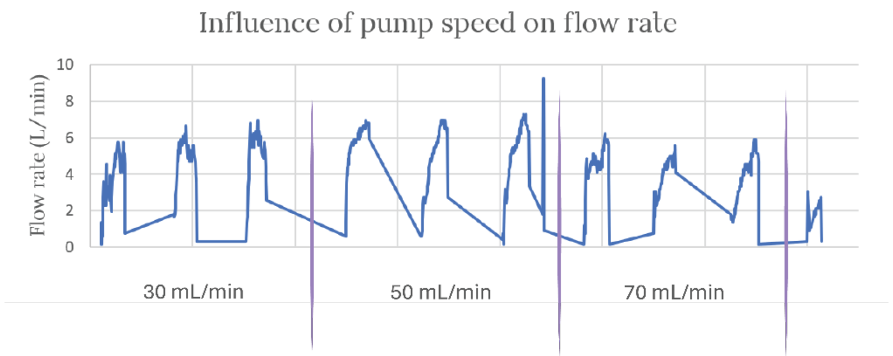


Figure 37: Influence of pump speed on steam flow rate using a thermocoil

Phase 6

The video analysis of different nozzles showed that smaller nozzles induce higher amounts of turbulence than larger nozzles with the same heating element settings (Figure 38 and 39). Reasons for this phenomenon will be further explored in the next chapter.

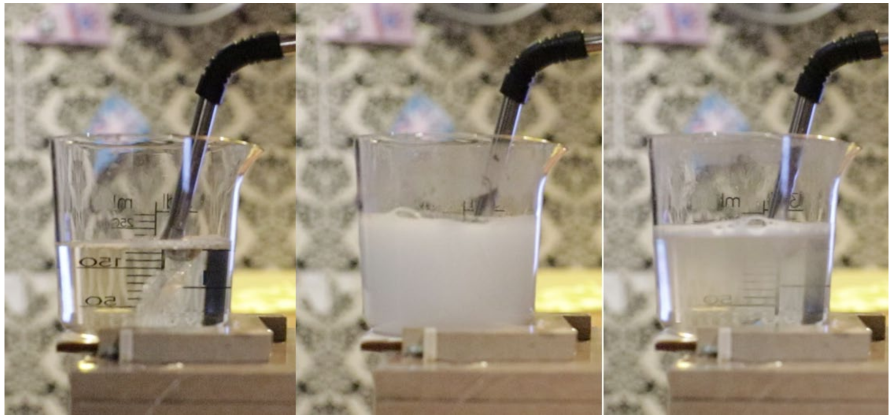


Figure 38: Turbulence induced by a single hole nozzle with diameter of 3.0mm of the thermocoil prototype.

Figure 39: Turbulence induced by a single hole nozzle with diameter of 1.5mm of the thermocoil prototype.

4.4.3 Conclusion

From this study it has become clear that the boiler elements perform significantly better than the flow through heating elements. The boilers approach the performance of the commercial espresso machines evaluated in the café machine performance study. Due to this performance, boilers have been identified as the heating technology for the concept that is being developed.

This another decision, the choice of the size of the boiler. The performance of the boilers is very similar. Other important factors in the selection of the technology are the size of the element and the heat-up time. A smaller size is desired, looking at wish E1 in the list of requirements. With a smaller heating element, the size of the entire product can be smaller. The heat-up time should also be a short as possible according to the list of requirements (wish A7). All information combined, concept will be built around the 500mL boiler.

An interesting insight into the performance difference between the two boilers is that it is that the large boiler can more quickly dissipate the heat to the liquid inside the boiler due to more surface area, see Figure 23. This design detail could explain the difference in performance between the 800mL and 500 mL boiler. Further development may include the design of a new boiler with optimized heating element surface area.

4.5 Nozzle design

4.5.1 Operational parameters

The goal with nozzle design is to identify nozzle designs that have the best balance between fluid heating time, steam velocity and control all with the goal of creating smooth microfoam. During the development, the list of requirement must be taken into account. The following requirements are applicable to the design of the nozzle:

A6	The product must be able to heat 200mL of water from 7 to 60 °C in approximately 20 seconds
A11	Product must retain a relatively constant steam flow with maximum average reduction in steam flow of 12%
A12	Product must not dilute the milk with water by more than 15%

4.5.2 Patent research

Patent research conducted to find current inventions in the development area of nozzle design for steam wands used for preparation of espresso based milk drinks. Three interesting patents (Figure 40) were identified showcasing the implementation of different nozzle geometries on the performance and/or user experience of the operation of the steam wand in (consumer) espresso machines.

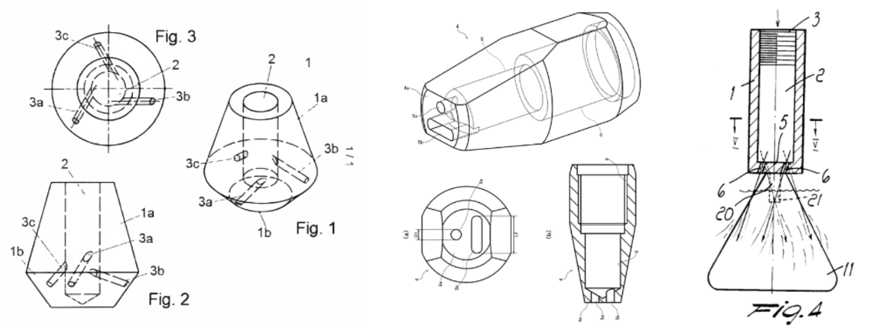


Figure 40: Identified patents regarding steaming nozzles for milk foaming application. From left to right: ITMC20130006U1, WO2010052966A1, EP0509505A2

The patents identify multiple problems with current nozzles designs offered in both commercial and consumer steam wands:

- The intensity of the steam jet is highly dependent on the capacity of the boiler built into the machine, which has significant impact on the performance of consumer espresso machines.
- Current nozzles cannot effectively generate cavitation, inducing inhomogeneous distribution of bubbles.
- The quality of milk froth is highly dependent on the operators skill.

The inventions intend to improve the process of creating milk foam using steam in the following ways:

- Creating a nozzle geometry so that the placement of the nozzle within the milk jug does not effect frothing quality, reducing the amount of skill required.
- Creating a nozzle geometry so that stable cavitation can occur during the aeration phase of milk frothing. This causes a more stable foam by reducing the change of bubble size over time.
- Optimizing the nozzle area so that the steaming time is reduced.

These patents serve as inspiration for the development of the nozzle for this concept. Furthermore, they identify points of interest to look into when evaluating the nozzles prototypes.

4.5.3 Nozzle area optimization

The area of the nozzle plays a crucial role in the overall efficiency of the system, as it directly influences the maximum mass flow rate. For optimal performance, the flow rate should be maximized to reduce the milk heating time while maintaining a stable and predictable flow rate for more control, improving the steaming experience.

High mass flow rate can be achieved by increasing the nozzle size. However, when a too large nozzle area is used, the mass flow rate is above the flow rate that can be supported by the heating element. This leads to a sudden decrease in flow rate and reduced steam velocity. This not a desirable situation as it increases the maximum bubble size in the foam, possibly leading to visible bubbles and reduces the stability and predictiveness of the system, making it harder to operate.

The ideal condition is achieved when the nozzle operates at it’s chocking point. This point is where the heating element can produce slightly more steam stand is being ejected from the nozzle. In this situation the pressure difference at the point of the nozzle is the highest To identify the best settings for this concept, a theoretical model has been developed and subsequently validated through empirical testing.

Theoretical model

A theoretical model is constructed based on the system model created in chapter 3.4.

1. Determining the maximum mass flow rate for different steam temperatures based on the power rating of the heating element using the following equation:

$$Q = \frac{Power_{HE}}{Enthalpy} * 3600$$

   The output of the equation is expressed in kg/hour, similar to the output of the model of paragraph 3.4. For the ease of this calculation, it is assumed that the boiler operates at an efficiency of 100% and that perfectly saturated steam is created.

2. Using the equation for the steam flow through an orifice, the flow rate is determined based on the input of different temperatures of steam and different nozzle diameters. A screenshot of the output of the model is presented in Figure 41.

1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.09
0.25	0.29	0.32	0.36	0.40	0.45	0.49	0.54	0.59	0.64	0.70	0.75	0.81	0.87	0.94	1.00
0.36	0.41	0.46	0.51	0.57	0.63	0.70	0.77	0.84	0.91	0.99	1.07	1.16	1.24	1.33	1.43
0.44	0.50	0.56	0.63	0.71	0.78	0.86	0.95	1.03	1.13	1.22	1.32	1.42	1.53	1.64	1.76
0.51	0.58	0.66	0.74	0.82	0.91	1.00	1.10	1.20	1.31	1.42	1.54	1.66	1.78	1.91	2.05
0.58	0.66	0.74	0.83	0.92	1.02	1.13	1.24	1.36	1.48	1.60	1.73	1.87	2.01	2.15	2.31
0.64	0.72	0.82	0.92	1.02	1.13	1.25	1.37	1.50	1.63	1.77	1.91	2.06	2.22	2.38	2.55
0.69	0.79	0.89	1.00	1.11	1.23	1.36	1.49	1.63	1.78	1.93	2.08	2.25	2.42	2.59	2.77
0.75	0.85	0.96	1.08	1.20	1.33	1.47	1.61	1.76	1.92	2.08	2.25	2.42	2.61	2.80	2.99
0.80	0.91	1.03	1.15	1.28	1.42	1.57	1.72	1.88	2.05	2.22	2.41	2.59	2.79	2.99	3.20
0.85	0.97	1.09	1.23	1.37	1.51	1.67	1.83	2.00	2.18	2.37	2.56	2.76	2.97	3.18	3.41
0.90	1.03	1.16	1.30	1.45	1.60	1.77	1.94	2.12	2.31	2.51	2.71	2.92	3.14	3.37	3.61
0.95	1.08	1.22	1.37	1.53	1.69	1.87	2.05	2.24	2.44	2.64	2.86	3.08	3.32	3.56	3.81
1.00	1.14	1.29	1.44	1.61	1.78	1.96	2.15	2.35	2.56	2.78	3.01	3.24	3.49	3.74	4.00
1.05	1.19	1.35	1.51	1.68	1.87	2.06	2.26	2.47	2.69	2.92	3.15	3.40	3.66	3.92	4.20
1.10	1.25	1.41	1.58	1.76	1.95	2.15	2.36	2.58	2.81	3.05	3.30	3.56	3.83	4.10	4.39
1.15	1.30	1.47	1.65	1.84	2.04	2.25	2.47	2.70	2.94	3.18	3.44	3.71	4.00	4.29	4.59
1.20	1.36	1.53	1.72	1.92	2.12	2.34	2.57	2.81	3.06	3.32	3.59	3.87	4.16	4.47	4.78
1.24	1.42	1.60	1.79	2.00	2.21	2.44	2.68	2.92	3.18	3.45	3.74	4.03	4.33	4.65	4.97

Figure 41: Output of the model for determining the optimal nozzle area.

3. From this output, the optimal nozzle size can be selected. The optimal nozzle diameter is the nozzle that allows slightly less mass flow rate, than the maximum determined in step 1. The optimal nozzle diameters are highlighted in blue (Figure 41).
4. A prediction of the velocity of the steam leaving the nozzle can also be calculated. To do so, the equations described by Babu (2021) are used.

From this nozzle we learn the following for the development of the final prototype to be delivered:

- At higher temperatures, smaller nozzles must be used to provide optimal mass flow rate. This is due to the higher pressure difference at higher temperatures.
- The velocity of the steam output increases with the increase of temperature and the reduction of nozzle diameter.

High velocity is something we want in the development, as this determines the maximum size of bubbles in the foam. The high temperature that is associated with the smaller nozzle also has its drawbacks. A higher steam temperature requires a higher boiler temperature, which leads to more heat losses. Therefore it is interesting to determine the optimal balance between steam velocity and heat losses, this can be achieved through empirical testing of prototypes in a later development stage.

Empirical testing

As before, a theoretical model in fluid mechanics involving turbulent can provide a starting point for testing and development, however due to the nature of turbulent flow it can only approach reality. In this part of the optimization of nozzle diameter, nozzles with different diameters are evaluated on boiler temperature response and the flow rate visible. The results of testing the different nozzles for boiler temperature over time are depicted in Figure 42.

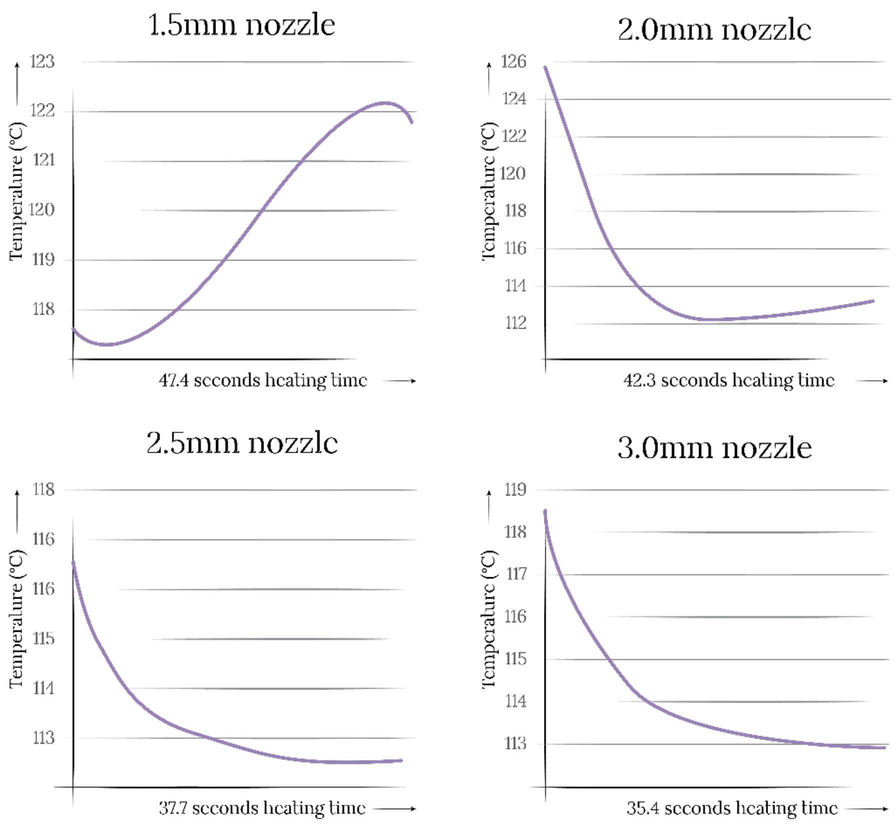


Figure 42: Influence of nozzle size on boiler temperature during steaming.

In the study, the target temperature of the boiler was set to 122 °C, equivalent to 1.0 barG of pressure. The steam was released into a pitcher containing 200mL of milk to determine the temperature change the nozzles can achieve.

From the results we can determine that the 1.5mm nozzle is definitely chocked for the required pressure. The temperature, after an initial drop recovers and exceeds the target temperature. Most likely, this nozzle can steadily operate at temperatures above 122 °C since the heating element was modulating around the target temperature. The other nozzles did not show a similar temperature recovery as the 1.5mm nozzle.

The results also show a limitation of boiler control based on temperature and such sensors. Temperature sensors have a thermal mass, which are slow to respond to sudden temperature changes. This induces a delay in the control of the prototypes. Furthermore, the temperature of the steam is highly dependent on the location of the temperature sensor within the system. It could be that the steam leaving the nozzle is much cooler than the temperature reading of the boiler.

In saturated and unsaturated steam systems, the temperature and pressure are dependent variables of each other. Pressure has the advantages that it is the same everywhere within the vessel and that the pressure change is instant allowing for faster response of the control system. In future development, I would advise to try implementing a pressure sensor instead of the current NTC.

4.5.4 Design considerations

The mass flow rate – determining the heating capacity – and the nozzle area determine the flow profile of the system, but other factors can be influenced too, namely nozzle geometry and the material the nozzle is made out of. Both of these factors can influence the experience of using the nozzle on the aspects of vortex control and machine cleaning. This chapter focusses only on the development of nozzle geometry because this could influence the milk foam quality.

The material choice is left for a later stage of product development, closer to the production stage of the product. However, what is important to the choice of such a material is that it has a low thermal conductivity and material hardness, surface finish and of course food safety.

Low thermal conductivity is desirable as current nozzles made out of stainless steel get really hot during the steaming process, much hotter than the prescribed maximum 65 °C for frothing process. This could possibly influence the organoleptic properties of the milk and makes the cleaning of the nozzle harder due to milk residue caking up on the nozzle.

The surface finish also impacts the ease of cleaning of the nozzle with a smoother surface finish being easier to clean than a more textured surface. A material with high hardness is desired for the longevity of the nozzle. Lastly, since this part of the machine comes in contact with food, it must be made out of a food safe material.

Nozzle geometry is a rather abstract term and in this thesis it is referred to the shape, direction and amount of the nozzle holes within the nozzle body. By changing these parameters, the way the steam interacts with the milk can be changed. This can lead to the development of a different vortex within the pitcher, leading to more control and a more uniform bubble size distribution.

The initial single hole nozzles (1.5, 2.0, 2.5 and 3.0 mm diameter) and a four hole nozzle with the single hole equivalent of a 3.0mm diameter were evaluated on the boiler prototype by a professional barista. During that test, the following insights were collected:

- The nozzle with multiple holes was easier to control than the single hole nozzles. The single hole nozzles caused a 'wave' in the pitcher, which could lead to spillage of milk.
- The single hole nozzle was the only nozzle that could achieve the desired milk foam quality, consisting of invisible bubbles.

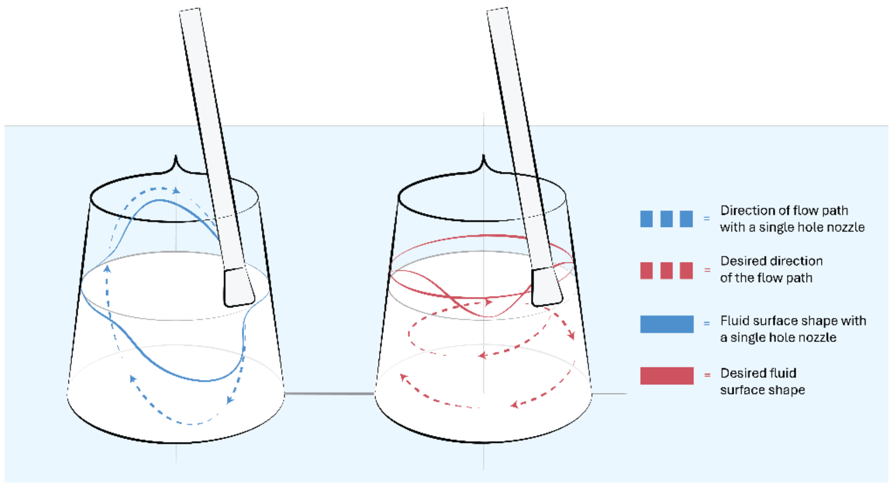


Figure 43: Comparison of a vortex created by a single hole nozzle (left) to the desired situation (right)

Figure 43 depicts two different types of vortex that can exist in the pitcher with milk. The left image shows the wave that is created in the pitcher with a single hole nozzle pointing in the direction of the steam wand. The right image shows the desired vortex for frothing milk. In this situation the surface of the fluid is spread evenly around the edges of the pitcher, above the initial height of the milk. In the centre of the pitcher, a dimple should form. When this situation is achieved, milk moves with high velocity through the pitcher and smoothly moves from the outside of the pitcher to the middle. That way, all big bubbles that might be formed during the aeration stage can be broken down and mixed into the milk.

The behaviour and idea of releasing the steam can be compared with the pouring of a beer. In that process, the spout is angled within the glass in such a way such as to prevent the beer from impacting the bottom of the glass aggressively. To achieve this, a redesign of the steam nozzle geometry is needed.

Multiple prototypes were created of nozzles that could possibly achieve this result. Drawings, pictures nor test results will be shared in this thesis as it contains sensitive information that could impact the competitive advantage of the product development and possible patent applications. What can be mentioned is that from a large sample of nozzles, two are identified for further development.

4.6 Final prototype evaluation

All nozzle prototypes were evaluated with professional baristas. The part of this evaluation that can be discussed in this thesis is the influence of the amount of nozzle holes. Two nozzle of equal nozzle area, but different amount of holes (Figure 44) were compared based on the formation of the vortex within the pitcher and the milk quality that could be achieved. The formation of the vortex is indicative of the steam velocity, high velocity steam will result in a very aggressive vortex.

Figure 44: Comparison of vortex creation between nozzles with equal nozzle area, but different sized holes

From this test, it has become clear that the nozzle with the two smaller diameter holes, can create a much more aggressive vortex. This means that a much higher velocity steam can be created using smaller holes, while retaining very similar mass flow rate.

These results also indicate that even on consumer espresso machines with less power than the prototype developed here, it might be possible to create high quality milk foam when being paired with an optimized nozzle for that specific machine.

The final prototype including the selected nozzle was evaluated with two baristas. One of the tests was conducted in a café (Figure 45), which allowed for the comparison of the performance of the prototype and the commercial espresso machine.

Figure 45: Testing of the development prototype with the final nozzle design being tested in situ, in the bottom right corner the milk foam quality is captured.

The other test was conducted in a quiet environment to allow for discussion on improvements for the nozzle. The goals of this evaluation was to determine the steaming performance of the prototype and to see whether a skilled barista would be able to create smooth microfoam with the prototype. The comments of the baristas during and after the evaluation were the following:

- Both baristas were surprised by the performance of the machine. This was immediately noticeable when they started steaming for the first time.
- The vortex that is created by the prototype is functioning so well, that even when you make a mistake during the aeration process, creating very large bubbles it is almost immediately nullified during the texturing phase.
- The texture of the milk is perfect, even after the milk was sitting for a long time, no bubbles were visible.

They also mentioned that the design of the product could be improved, which comprised of the following changes:

- The location of the nozzle is too low now. If a larger pitcher would be used, it would be very difficult to get the steam wand into the pitcher.
- A longer steam wand is desired, especially if larger amount of milk must be steamed, requiring a larger pitcher.

05.

Deliver

This chapter is the final chapter of this thesis. It describes the design considerations for the final prototype, which include user interfaces and other components. Furthermore, the chapter gives recommendations for further development of the concept and reflects on the design process that was followed during this thesis.

5.1 Design choices

The development stage has granted many insights into the performance of the many prototypes created for this thesis. This final part of the thesis focusses on the delivery of the final prototype. The goal of this prototype is to showcase the optimized performance of the concept. The prototype is a refinement of the concept that is developed during this thesis, including user interaction, further part selection and some design work.

5.1.1 User interaction

Up to now, the prototypes functioned only when they were connected to a computer. The prototype featured no user interface as the functions and needs for the information required is formed in a later stage of development. For the final prototype, short user research was conducted to determine what information users would like to receive from such a product. On a sub-forum of Reddit called r/espresso, users – mostly baristas and coffee enthusiasts – were asked what they paid attention to when using the steaming function on their espresso machines. The responses were quite clear:

- People only pay attention to what they can influence, on most espresso machines the only easily accessible part that is accessible is the nozzle. This confirms the wish stated by the baristas in the expert interview that the nozzles should be interchangeable.
- People have very little time to pay attention to the gauges on espresso machines during steaming, so they rarely pay attention to them.
- The only information that the target audience is interested in, is whether the machine is ready to be used.

From this, we can conclude that the interface should feature the following items:

- A gauge or display that shows the current pressure or readiness level of the machine.
- We also want the user to be able to change system parameters, such as the pressure in the boiler. Therefore, the product should have a button to change these parameters.
- Lastly, the switch for turning on the steam should be easily accessible.

The design of user interface that was created and prototyped is depicted in Figure 46. In the design it was important that it consists of an easy to understand interface and that it fits well in the design trends of the coffee market.

Figure 46: Prototype of the user interface for the final prototype

The interface features a 7-segment display for providing the user with the boiler pressure at which the boiler is set. A 7-segment display is a low cost solution and is featured on existing high-end espresso machines by Kees van der Westen and the recently released LaMarzocco Linea Mini. To the right of the 7-segment display is the potentiometer that can be used to change the boiler pressure.

The design also features an array of LEDs that indicate whether the heating element is ready for use and, if not, how far along in the heating cycle the boiler is. This is done by sequentially lighting up the LEDs based on the heating percentage of the boiler. If all lights are on, the product is ready to be used.

Lastly, the steam release switch is located on the left side of the user interface. This switch is located on the left side of the user interface, because most people are right hand dominated. It is expected that baristas hold the milk pitcher in their dominant hand, allowing the user to easily operate the steam release switch with their free left hand.

The interface was discussed with a barista during the last prototype evaluation. He simply mentioned that it displayed the required information for their liking, further mentioning that the interface is not that important as he never looks at the gauges on his espresso machine.

5.1.2 Water reservoir

The previous prototypes did not feature a water reservoir. For the final prototype it is important that it can be easily taken anywhere, after al it is a showcase of the possibilities of the product. To determine the size of the water reservoir, inspiration was taken from the design choices of espresso machines currently on the market.

High-end consumer espresso machines often feature a water reservoir that is 2-3 times the size of the boiler. That means that the water reservoir for this prototype should be at least 750 mL.

5.1.3 Pump selection

The pump used in the technology evaluation prototypes was switched out for a different pump. The new pump is still a reciprocating pump, a very cheap and reliable pump featured in most home espresso machines. However, the pump new pump is selected due its small size, trying to reduce the required space within the product as much as possible. Next to that, the pump is much quieter than the previous pump, which output 65 dB of noise. Table 6 depicts pump characteristics of the old (ULKA EP5) and the new pump (JYPC-2).

Table 6: Comparison of pump characteristics between the pumps of the development prototype and the final prototype.

	CEME ULKA EP5	Jiayin JYPC-2
Flowrate (mL/min)	650	90
Maximum pressure (bar)	15	3
Power (W)	48	16
Noise (dB)	65	38

5.1.4 Size determination

People want the product to require as little countertop space as possible, however not every dimension is equally important. Previous research during the BYS course has shown that the most important dimension is the width of the product, followed by the depth. Furthermore, according to the results of the discover phase, the product design should be both practical and visually appealing. Some sketches were created to identify interesting shapes for the final prototype (Figure 47).

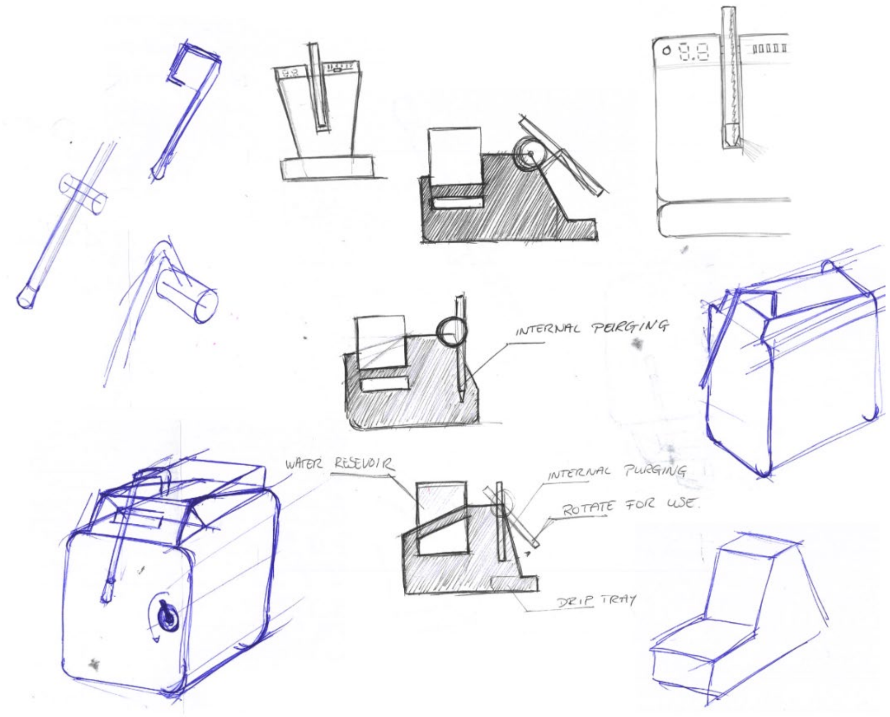


Figure 47: Concept sketches for the final prototype.

The final prototype will be delivered during the presentation of this thesis, but a preliminary comparison with the previous prototypes and the new design is depicted in Figure 48.

During the sketching, some ideas about the steam wand shape and positioning were formed. This was in response to the comment by the baristas on points of improvement for the prototype.

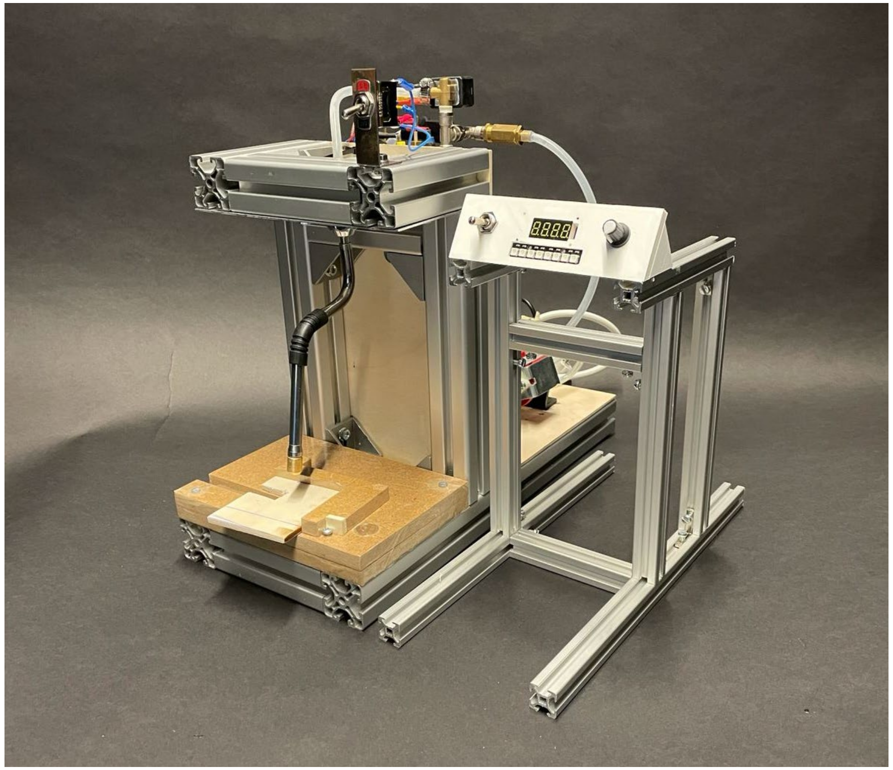


Figure 48: Size comparison between the previous prototype and the frame for the final prototype.

5.2 Recommendations

During this thesis, many improvements and areas of interest were noted. However, not all of these improvements could be evaluated in the limited amount of time available. Therefore, in this chapter the insights gathered will be discussed so that they can be tested and possibly implemented in later stages of development.

The first area of recommendations is around the boiler and the control of the heating element. The results from the integrated prototype evaluation suggested that controlling the boiler based on temperature is slow and possibly inaccurate. This is caused by the thermal mass of the sensor used and that temperature is location dependent. Suggestion for improvement would be to use a pressure sensor to provide data for the control system. However, pressure sensors that can operate at high temperatures are rather expensive. Therefore research must be conducted to determine whether a pressure sensor can provide a more stable heating platform that justifies the cost.

The second recommendation regarding the boiler is to look into the optimization of the heating element within the boiler. Through testing it was determined that the 800mL boiler could create a higher flow rate than the 500mL boiler, while both requiring the same amount of power. This is expected to be due to the increased surface area of the heating element in the larger boiler. Possibly, the performance of the smaller boiler can be improved if the heating element has a larger area that is in contact with the water in the boiler. It is therefore recommended to identify whether it is possible to source or develop such an element.

Boiler efficiency might also be improved by the addition of different insulation material. The current sleeve of insulation material does not cover the entire area of the boiler, which leads to more heat losses. I would suggest to identify by how much these losses can be reduced if more efficient insulation material is used.

The next area of recommendations is about the dryness of the system. Currently, approximately 1 gram of water is added to the milk when steaming. The average steaming time of 360 mL of milk is approximately 40 seconds, which means that there is about 11% adsorption of water. While this does meet the requirement stated in the List of Requirements the following changes are proposed; switching out the current piping for pipes made out of a material with low thermal conductivity. The same material could be used to create fittings for the system. By doing so, there is very little energy loss for the steam during the transportation from the boiler to the nozzle. It would also mean that no insulation needs to be added around these parts.

5.3 Process reflection

How did the selection of methods and approaches suit this phase of the design process? What if you had started prototyping earlier?

Now that we are at the end of the project, it is helpful to reflect on the path taken and choices that were made during this project. The reflection is even more important, as this project does not end with the writing of this thesis. The concept will be further developed over the next 6 months.

The project was started with a lot of enthusiasm and in my mind I already had the solution ready. The process of design and innovation does not work that way. It is important to create a holistic image of the problem and solution space before coming up with solutions. Choosing to work with the double diamond framework forced me to take a step back and first re-evaluate what was important to the users and what was already offered by other frothing technologies.

Looking back, the project could be moving extremely slowly during some parts of the thesis. At those points, I wished I had implemented the lean-startup approach. In these phases I was often stuck doing desk research, to find the last – tiny piece of the puzzle – that was missing to have complete understanding of a subject. Many times, this information did not prove critical and hypothesis about the subject was formed much earlier. If I would have gone out and talked to people, asked more people for help, the project would have moved on a lot quicker.

At times in the project I tried to make a perfect product, forgetting that this this thesis is only at the start of the development process with many iterations to come. An example of this was during the selection of pumps for the prototypes. I knew that I could create a prototype using a less ideal pump, that would be sufficient enough to evaluate the performance. However, I thought strived to find the optimal components for the product to function, forgetting it was just a prototype. In the end, it turned out that the heating element that required these specific pumps was not the optimal heating element, rendering all of the countless hours of research, part sourcing, talking to manufacturers and waiting for the shipment to arrive useless.

I am satisfied with the results of this project. I think the project has delivered a well functioning prototype, based on a lot of research, that will be the basis of further development. Next to that, I hope the prototype can let people experience the enjoyment of creating the same quality of milk foam as they are served in cafés. With that I hope that this product will one day be a succes.

Lastly, most valuable lesson I learned during this project, which I will try to keep in mind while designing a product and which I wish to relate to other designers (to-be) is the following:

"You are a designer! After gathering most of the information you are most likely able to fill in the blanks. During the process of gathering information you have had hunches, follow them, test them as quickly as possible!

Get away from that computer, talk to people and build the prototype that can evaluate your hypothesis with the least amount of effort.

That way you will be able to learn fast and gather more knowledge than you would otherwise have gathered."

Appendices

This chapter contains the references of this thesis as well as a guide to the appendices, attached to this thesis in another document.

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Other appendices

The other appendices can be found in the attached document called "Appendices". The following appendices are located in that file:

Appendix I	Comments gathered from Kickstarter
Appendix II	User group identification research
Appendix III	Expert interviews
Appendix IV	Theoretical system model
Appendix V	Dutch Norm - NEN-EN-IEC 60661:2014
Appendix VI	Café machine evaluation
Appendix VII	List of Requirements
Appendix VIII	Project brief