

Micro-brewery control strategy for the Raspberry Pi using a HERMS

By Schalk van Heerden

and Carl Sandrock



Heerden Process Engineering

South Africa

Version 0.1

2015

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

Should you wish to redistribute verbatim copies of this work, attribute me as follow:

This material was created by Schalk van Heerden and published freely under a Creative Commons Attribution license at <http://heerden.co.za>.

Should you wish to redistribute revised or remixed versions of this work, attribute me as follow: *This material is based on original writing by Schalk van Heerden, which was published freely under a Creative Commons Attribution license at <http://heerden.co.za>.*

If you would like to attribute me differently, contact me.

Preface

“Are you working on your Cherry Pie again,” she asks me. I was indeed busy configuring the Raspberry Pi to control my new fully automated brewery. My days of using malt extract and stirring a pot on the stove was over. I wanted to be a true artist and start all-grain brewing.

A Heat Exchange Recirculating Mash System (HERMS) was chosen as the perfect process to implement. For most home brewers, controlling the temperature is all that is needed, but I wanted to control as many variables as possible.

A control philosophy was developed for 12 steps in the HERMS stage. The fermentation stage required 5 steps, while a final clean-in-place stage required 11 steps. To achieve this, 28 inputs (temperature, level, flow) and outputs (pumps, valves, heating elements, motors) was needed.

The Raspberry Pi is a microcomputer, running the Linux operating system. It is low cost and supports other low cost instruments. A circuit board was designed to facilitate the connection between the Raspberry Pi and instruments. A decentralised control strategy with Proportional Integral Differential (PID) control, and the timing sequence for switching the equipment, was executed with Python code. It was also setup to serve as a control panel that could be accessed remotely over the internet. All the major electrical components were safely enclosed in a control box.

Magnetically coupled pumps where selected to drive the process liquids and solenoid valves controlled the flow. Three stainless steel vessels were used and equipped with fittings to connect to the silicon piping system. A custom actuated control valve was also designed.

There are several components still missing in the design and an advanced process control strategy will be considered for the future.

This is how the Cherry Pie Brewery was born.

Acknowledgment

Without the wealth of knowledge available in the home brewing and electronic community, this design guideline would not have been possible.

Contents

Preface	i
Acknowledgment	ii
Contents	iii
List of Figures	vi
List of Abbreviations	viii
1 Introduction	2
2 Process description	3
2.1 Sugar extraction	3
2.2 Fermentation	4
2.3 Auxiliaries	4
3 Control philosophy	6
3.1 HERMS	7
3.1.1 Open cold water tap	8
3.1.2 Fill Hot Liquor Tank (HLT) with cold water	9
3.1.3 Fill Kettle (KET) with cold water	10
3.1.4 Heat process water	11
3.1.5 Fill Mash Lauter Tun (MLT) from KET	12
3.1.6 Add grain	13
3.1.7 Mash	14
3.1.8 Mash out	15
3.1.9 Sparge	16
3.1.10 Boil wort	17
3.1.11 Add hops	18
3.1.12 Chill wort and fill Fermenter (FER)	19
3.2 Fermentation	20
3.2.1 Cool wort	21
3.2.2 Pitch yeast	22
3.2.3 Control temperature	23
3.2.4 Add priming sugar	24
3.2.5 Bottle beer	25

3.3	Clean In Place (CIP)	26
3.3.1	Add CIP solution to HLT	27
3.3.2	CIP for HLT section	28
3.3.3	Fill MLT with CIP solution	29
3.3.4	CIP for MLT section	30
3.3.5	Fill KET with CIP solution from HLT	31
3.3.6	Fill KET with CIP solution from MLT	32
3.3.7	Reconfigure Heat Exchanger (HX) and drain piping	33
3.3.8	CIP for KET section	34
3.3.9	CIP drain	35
3.3.10	Open cold water	36
3.3.11	Fill HLT with water and restart sequence	37
4	Mechanical design	38
4.1	Vessel and piping overview	38
4.2	Control valve assembly	40
4.3	Probes	41
4.4	Vessel fittings	42
4.5	Pumps and valves	43
4.6	Heat exchangers	44
5	Electrical design	45
5.1	Overview	46
5.2	Microcomputer	47
5.2.1	Raspberry Pi	48
5.3	High voltage system	50
5.3.1	Power supply	50
5.3.2	Heating element	50
5.3.3	Relays	50
5.4	Low voltage system	50
5.4.1	Flow meter	50
5.4.2	Temperature probe	51
5.4.3	Level sensor	51
5.4.4	Solenoid valve	51
5.4.5	Stepper motor	52
5.5	Control box	52
6	Software design	54
6.1	Operating system setup	54
6.2	Control system	54
6.2.1	RaspPiBrew	55
6.2.2	The repository	56
7	Process control design	57
7.1	Controller design	57
8	Recommendations	58

List of Figures

2.1	Brewery Piping and Instrumentation Diagram (P&ID)	4
2.2	Brewery P&ID	5
3.1	Open cold water tap	8
3.2	Fill HLT with cold water	9
3.3	Fill KET with cold water	10
3.4	Fill MLT from KET	11
3.5	Fill MLT from KET	12
3.6	Add grain	13
3.7	Mash	14
3.8	Mash out	15
3.9	Sparge	16
3.10	Boil wort	17
3.11	Fill FER with wort	18
3.12	Chill wort and fill FER	19
3.13	Cool wort	21
3.14	Pitch yeast	22
3.15	Control temperature	23
3.16	Add priming sugar	24
3.17	Bottle beer	25
3.18	Add CIP solution to HLT	27
3.19	CIP for HLT section	28
3.20	Fill MLT with CIP solution	29
3.21	CIP for MLT section	30
3.22	Fill KET with CIP solution from HLT	31
3.23	Fill KET with CIP solution from MLT	32
3.24	Reconfigure HX and drain piping	33
3.25	CIP for KET section	34
3.26	CIP drain	35
3.27	Open cold water	36
3.28	Fill HLT with water and restart sequence	37
4.1	Vessel and piping	38
4.2	Control valve	40
4.3	Temperature probe	41
4.4	Vessel fittings	42
4.5	Pump curve	43

5.1	Electrical wiring	46
5.2	Raspberry Pi Model B+ pin layout	49
5.3	Cherry Pie circuit board	52
5.4	Control box	53
6.1	RasPiBrew control panel	56

List of Abbreviations

AC	Alternating Current
AX	Auxiliary equipment
BIAB	Brew An A Bag
CP	Pump
CIP	Clean In Place
CV	Control Valve
DC	Direct Current
FER	Fermenter
GFI	Ground Fault Interrupter
GPIO	General Purpose Input Out
HDPE	High-density Polyethylene
HE	Heating Element
HERMS	Heat Exchange Recirculating Mash System
HLT	Hot Liquor Tank
HX	Heat Exchanger
IMC	Internal Model Control
IP	Internet Protocol
KET	Kettle
LE	Level Sensor
MLT	Mash Lauter Tun
MPC	Model Predictive Control
MR	Motor

OP	Control Module
P&ID	Piping and Instrumentation Diagram
PID	Proportional Integral Differential
PLC	Programmable Logic Controller
PV	Process Variable
RIMS	Recirculating Infusion Mash System
SP	Setpoint
SS	Stainless Steel
SSL	Secure Sockets Layer
SSR	Solid State Relay
TE	Thermocouple
TK	Tank
VNC	Virtual Network Computing

Chapter 1

Introduction

According to The History Channel (2011), the technological, social, and economical development of the society is linked to mankind's desire to brew more beer. The beer brewing process dates back thousands of years and every culture has their own refined version. In simplified terms, beer is produced from four main ingredients: a grain (primarily barley), hops, yeast and water; water is the liquid medium. Sugar is extracted from the grain and hops adds to the bitter taste. Yeast is added to this mixture and left to ferment at a suitable temperature.

Commercially, beer continues to be a booming industry. ReportLinker (2014) projects that by 2015, 183 million litres will be produced, which will make the industry worth \$523.5 billion. A sector of this industry that is also gaining market share annually, is craft or micro brewing. They are categorised by traditional brewing processes and independently owned. The main problem that craft brewers experience is producing a consistent brand of beer. This work will implement a control strategy, to minimise this problem.

The rise in popularity of the Raspberry Pi microcomputer cannot be claimed by beer, but this computer, and similar inexpensive instruments will be used to implement the control strategy for a fully automated micro-brewery. The production capacity will be 20 litres per batch.

In order to explain the control strategy in more detail, the control philosophy will firstly be explained, with specific emphasis on sugar extraction, fermentation and the cleaning process. Next, the design of the mechanical, electrical and software systems, as well as the process control will be discussed. The design guideline will conclude with a discussion on recommendations for future improvements.

Chapter 2

Process description

This chapter will give a general description of the brewing process, with a focus on the sugar extraction process.

It is beyond the scope to describe the scientific details of every brewing process and therefore resources such as Palmer (2004) should be consulted.

The brewery will use batch processes and all its steps will be fully automated. Once raw materials are added, the controller will take charge of the whole operation until the final product (beer) is in a keg. Manual steps, like adding the raw material at specific time intervals, are however still required.

2.1 Sugar extraction

Get a new name for this section.

Heat is required in a MLT vessel to convert the grain to sugar, in a process called mashing; the product is called the wort. It is essential to control the temperature of this process to ensure that the correct enzymes are activated, which will release the required sugars. There are several methods to achieve optimal temperature control in a micro-brewery process. The two prominent processes are Recirculating Infusion Mash System (RIMS) and Heat Exchange Recirculating Mash System (HERMS). In both processes, the wort is recirculated with a pump through the MLT and an heat exchange device. RIMS uses an electric heater inline with the recirculation system. HERMS uses a heat exchange coil that is submerged in a HLT. The wort is then recirculated through the coil. This design will use a HERMS, as it is more energy and equipment efficient (BrewersFriend, 2009).

A piping and instrumentation diagram of the brewery is given in Figure 2.1.

The third vessel used is the KET. It is used to preheat the water for mashing and finally to boil the wort. The hops is also added in this vessel.

If the production capacity of the brewery is 1, the ideal ration of vessel volumes for the HLT, MLT and KET is 2:0.8:1.5 (The Electric Brewery, 2014).

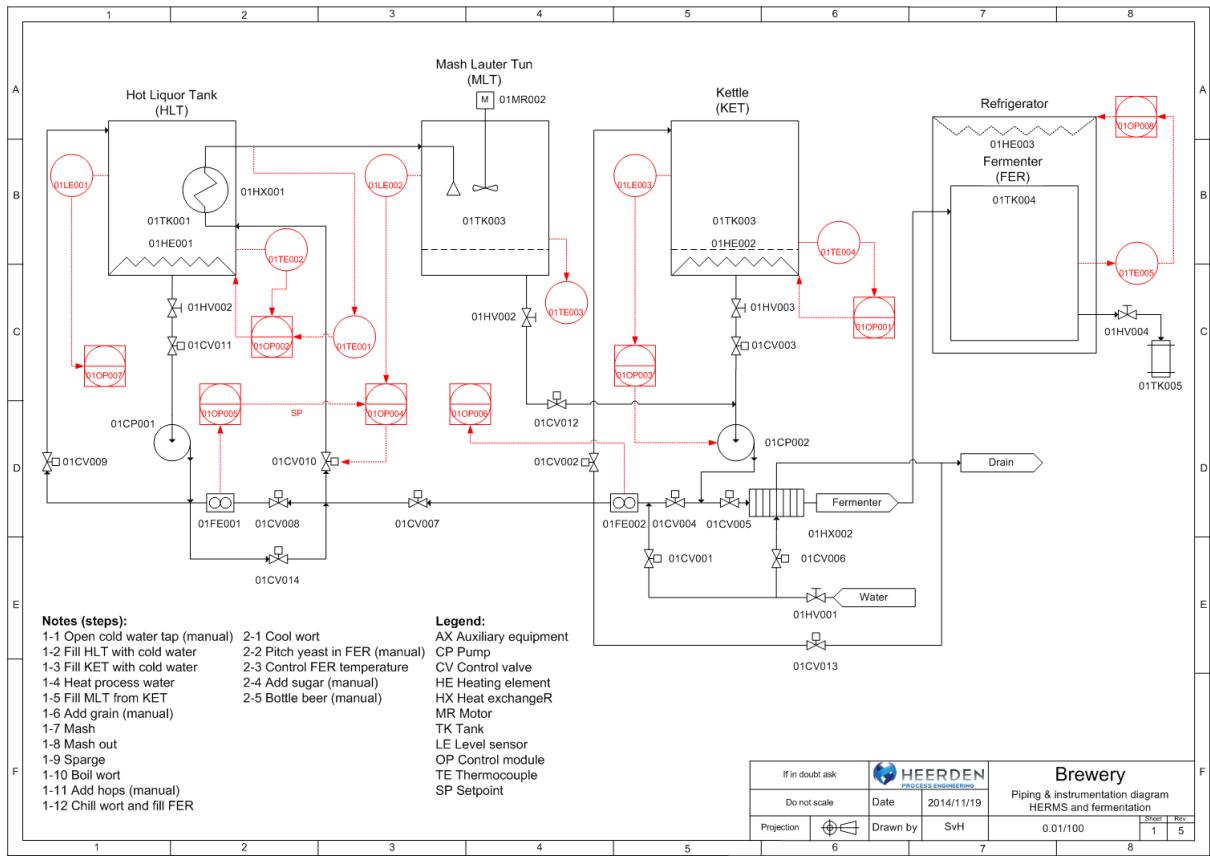


Figure 2.1: Brewery P&ID

2.2 Fermentation

2.3 Auxiliaries

In the next chapter, the complete control philosophy will be given for the HERMS, fermentation process and a CIP process.

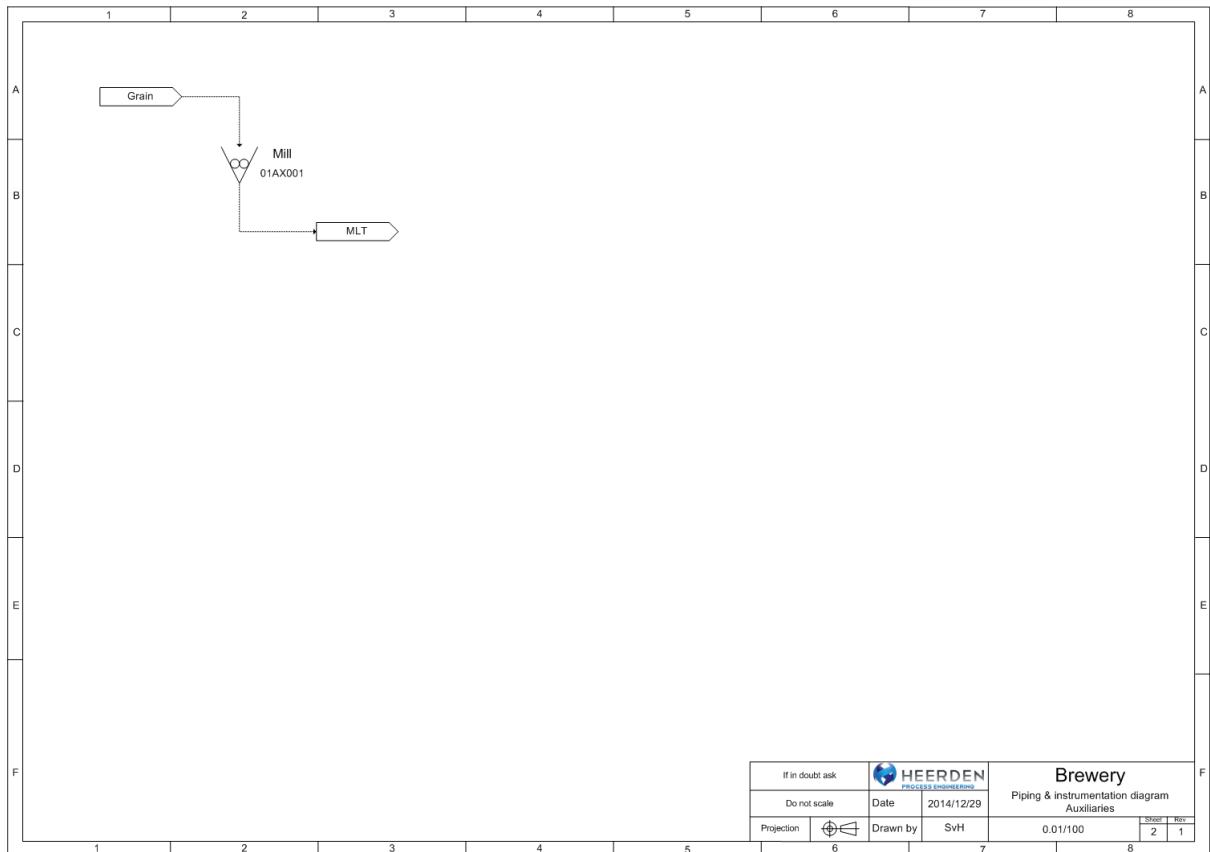


Figure 2.2: Brewery P&ID

Chapter 3

Control philosophy

The control philosophy will identify the important control objectives in every step and the instruments that are required. The three major process steps are:

1. HERMS
2. Fermentation
3. CIP

On the diagrams the key for all the brewing steps are as follows:

Red: instrumentation

Blue: cold water

Orange: wort

Brown: raw material

Purple: cleaning agent

Asterisk (*): manual step

3.1 HERMS

There are twelve process steps for the extraction of sugar and preparation of the wort:

1. Open cold water tap*
2. Fill HLT with cold water
3. Fill KET with cold water
4. Heat process water
5. Fill MLT from KET
6. Add grain*
7. Mash
8. Mash out
9. Sparge
10. Boil wort
11. Add hops*
12. Chill wort and fill FER

A summary of all these processes is given in Table 3.1.

Table 3.1: Step 1 sugar extraction process summary

Step	Description	Mode	Temperature (°C)				Level (mm)			Flow		Heat element		Pumps													
			TE001	TE002	TE003	TE004	LE001	LE002	LE003	FE001	FE002	HE001	HE002	CP001	CP002												
1-1	Open cold water valve	Manual	NR	NR	NR	NR	NR	NR	NR	NR	NR	C	C	C	C												
1-2	Fill HLT with cold water	Auto	LE001	NR	MR	NR	NR	400	NR	NR	NR	C	C	C	C												
1-3	Fill KET with cold water	Auto	LE003	NR	MR	NR	MR	MR	NR	NR	MR	C	C	C	C												
1-4	Heat process water	Auto	TE002 & TE004	NR	65	NR	65	65	MR	NR	NR	M	M	C	C												
1-5	Fill MLT from KET	Auto	TE001	65	MR	MR	MR	MR	200	MR	MR	M	M	C	C												
1-6	Add grain	Manual	Control panel	65	MR	MR	MR	MR	MR	NR	NR	M	M	C	O												
1-7	Mash	Auto	90 min	65	MR	MR	NR	MR	MR	MR	NR	M	M	C	O												
1-8	Mash out	Auto	TE001	75	MR	MR	NR	MR	MR	NR	NR	M	M	C	O												
1-9	Sparge	Auto	LE001	MR	MR	MR	MR	MR	MR	MR	MR	M	M	C	O												
1-10	Boil wort	Auto	60 min	NR	NR	NR	MR	NR	NR	MR	MR	M	M	C	O												
1-11	Add hops	Manual	Control panel	NR	NR	NR	MR	NR	NR	MR	NR	M	M	C	C												
1-12	Chill wort and fill FER	Auto	LE003	NR	MR	NR	MR	MR	NR	MR	MR	C	C	C	O												
Valves																											
		Mode	CV001	CV002	CV003	CV004	CV005	CV006	CV007	CV008	CV009	CV010	CV011	CV012	CV013	HV001											
1-1	Open cold water valve	Manual	C	C	C	C	C	C	C	C	C	C	C	C	C	O											
1-2	Fill HLT with cold water	Auto	LE001	O	C	C	C	C	C	O	O	M	C	C	C	O											
1-3	Fill KET with cold water	Auto	LE003	O	M	C	C	C	C	C	C	C	C	C	C	O											
1-4	Heat process water	Auto	TE002 & TE004	C	C	C	C	C	C	C	C	C	C	C	C	C											
1-5	Fill MLT from KET	Auto	TE001	O	C	O	O	O	C	C	C	C	C	C	C	C											
1-6	Add grain	Manual	Control panel	O	C	C	O	C	C	O	C	C	O	O	C	C											
1-7	Mash	Auto	90 min	C	C	C	O	C	C	O	C	C	O	O	C	C											
1-8	Mash out	Auto	TE001	C	C	C	O	C	C	O	C	C	O	O	C	C											
1-9	Sparge	Auto	LE001	C	O	C	O	C	C	O	C	C	M	O	O	C											
1-10	Boil wort	Auto	60 min	C	C	C	C	C	C	C	C	C	C	C	C	C											
1-11	Add hops	Manual	Control panel	C	C	C	C	C	C	C	C	C	C	C	C	C											
1-12	Chill wort and fill FER	Auto/Manual	LE003	C	C	O	C	O	O	O	O	O	C	C	O	O											
Key																											
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 10px; height: 10px; background-color: #008000;"></td><td>Open/on</td></tr> <tr> <td style="width: 10px; height: 10px; background-color: #800000;"></td><td>Closed/off</td></tr> <tr> <td style="width: 10px; height: 10px; background-color: #FF8C00;"></td><td>Modulated</td></tr> <tr> <td style="width: 10px; height: 10px; background-color: #00FFFF;"></td><td>[Value] Setpoint</td></tr> <tr> <td style="width: 10px; height: 10px; background-color: #008000;"></td><td>MR Monitor</td></tr> <tr> <td style="width: 10px; height: 10px; background-color: #800080;"></td><td>NR Not Required</td></tr> </table>																	Open/on		Closed/off		Modulated		[Value] Setpoint		MR Monitor		NR Not Required
	Open/on																										
	Closed/off																										
	Modulated																										
	[Value] Setpoint																										
	MR Monitor																										
	NR Not Required																										

3.1.1 Open cold water tap

Table 3.2: Step 1-1 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	OFF	-	-
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-

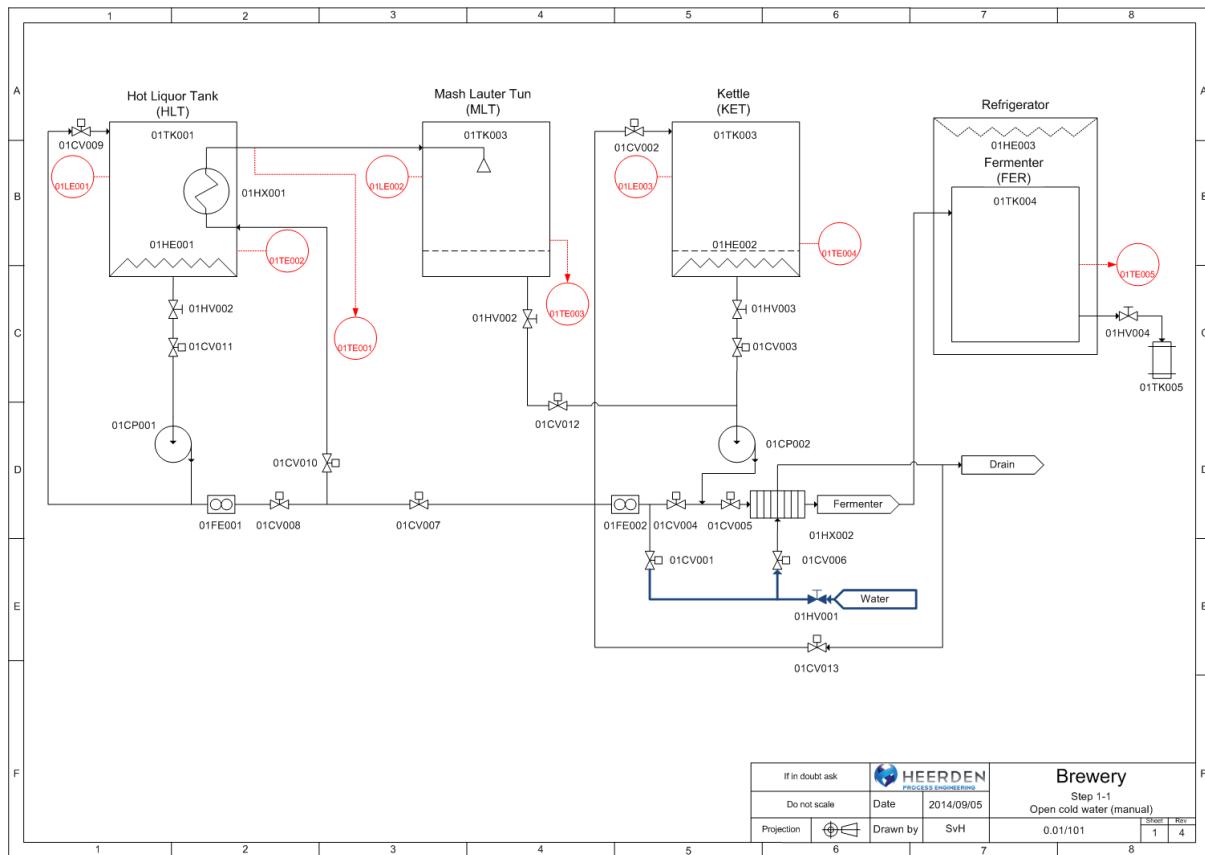


Figure 3.1: Open cold water tap

3.1.2 Fill HLT with cold water

Table 3.3: Step 1-2 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	OFF	-	-
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-
Valve 9	01CV009	400mm	Level 1	01LE001

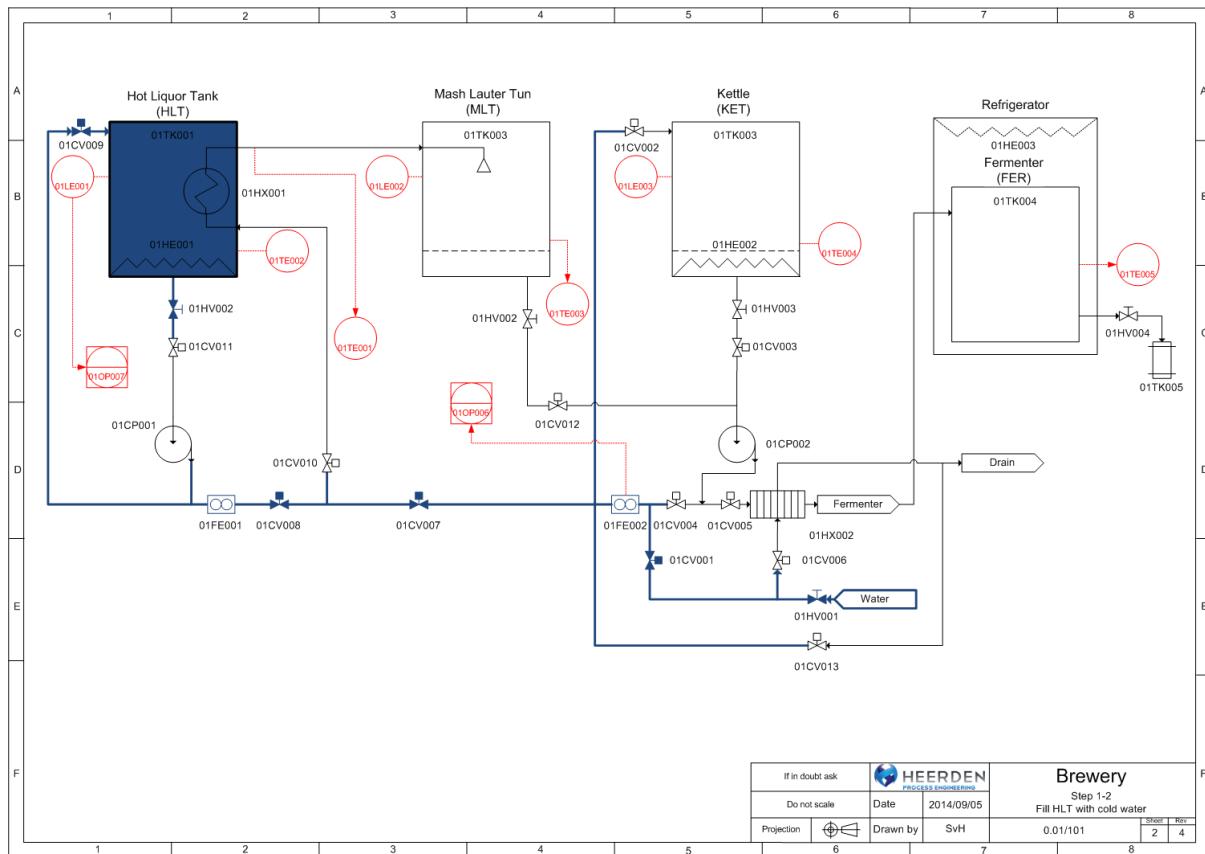


Figure 3.2: Fill HLT with cold water

3.1.3 Fill KET with cold water

Table 3.4: Step 1-3 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	OFF	-	-
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-
Valve 2	01CP002	200mm	Level 3	01LE003

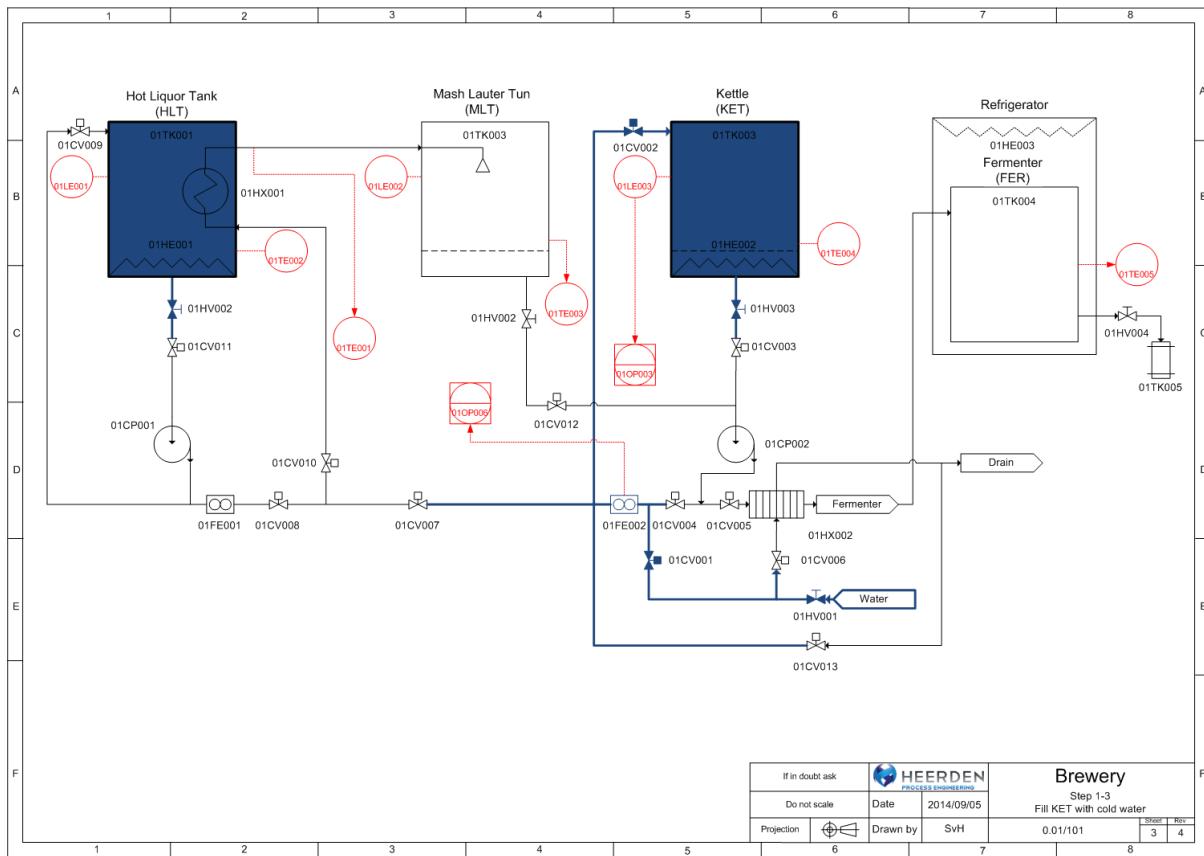


Figure 3.3: Fill KET with cold water

3.1.4 Heat process water

Table 3.5: Step 1-4 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	65°C	Temperature 2	01TE002
KET element	01HE002	65°C	Temperature 4	01TE004
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-

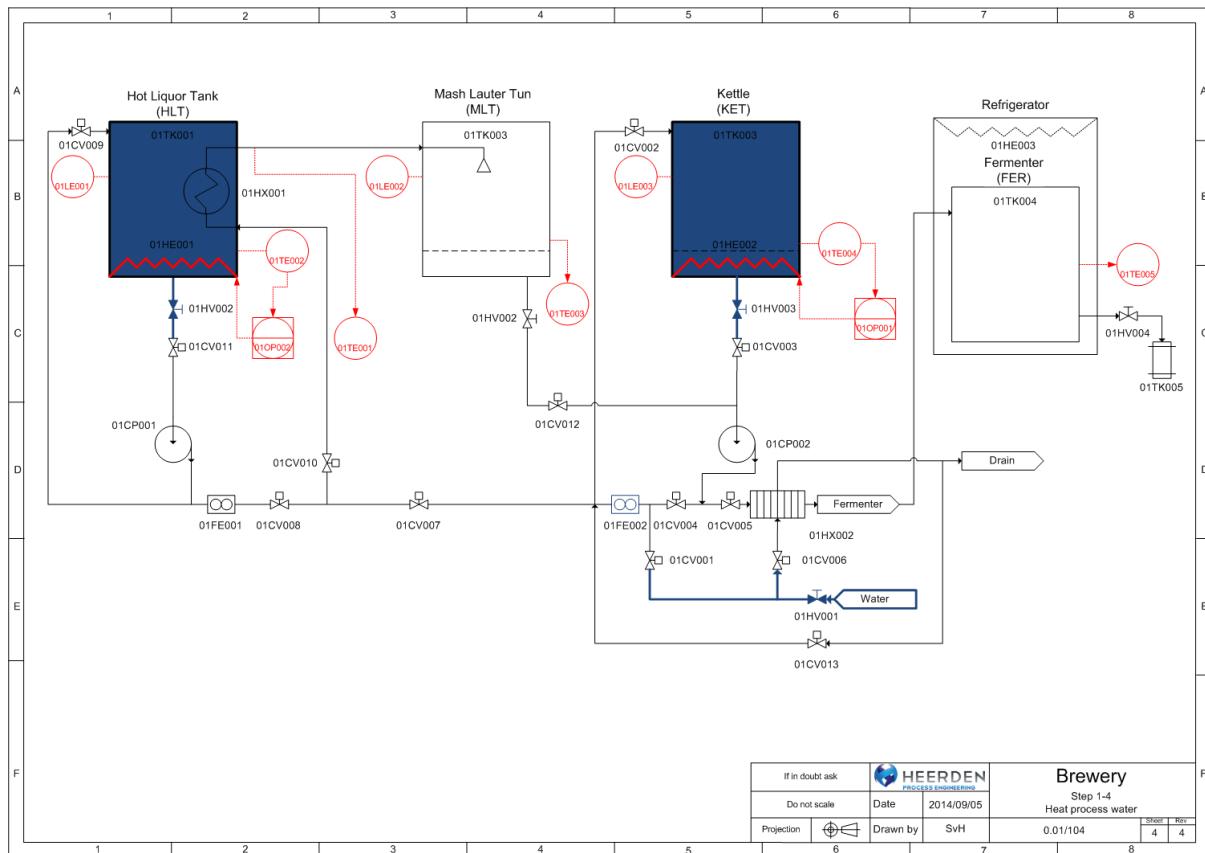


Figure 3.4: Fill MLT from KET

3.1.5 Fill MLT from KET

Table 3.6: Step 1-5 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	65°C	Temperature 2	01TE002
KET element	01HE002	OFF	-	-
Pump 1	01CP001	ON	-	-
Pump 2	01CP002	OFF	-	-
Valve 7	01CV009	200mm	Level 2	01LE002

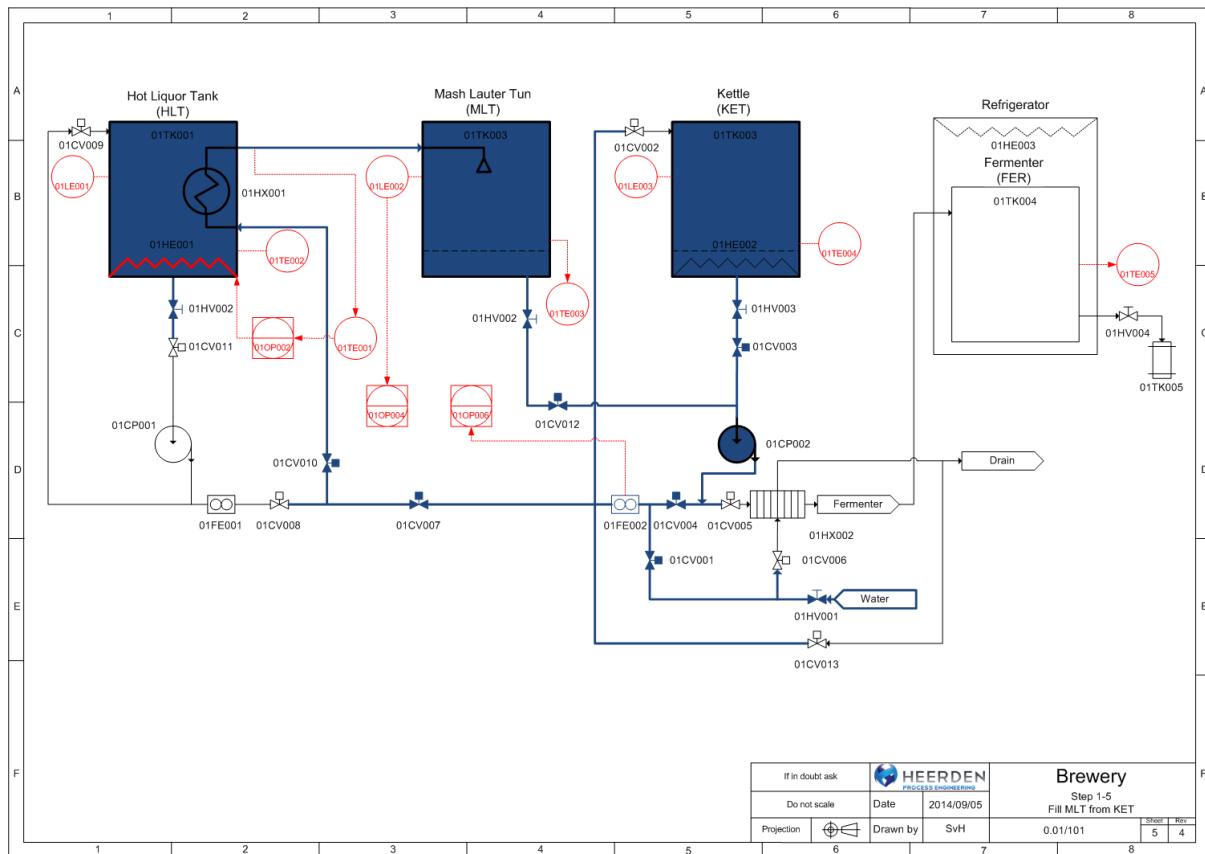


Figure 3.5: Fill MLT from KET

3.1.6 Add grain

Table 3.7: Step 1-6 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	65°C	Temperature 2	01TE002
KET element	01HE002	OFF	-	-
Pump 1	01CP001	ON	-	-
Pump 2	01CP002	OFF	-	-

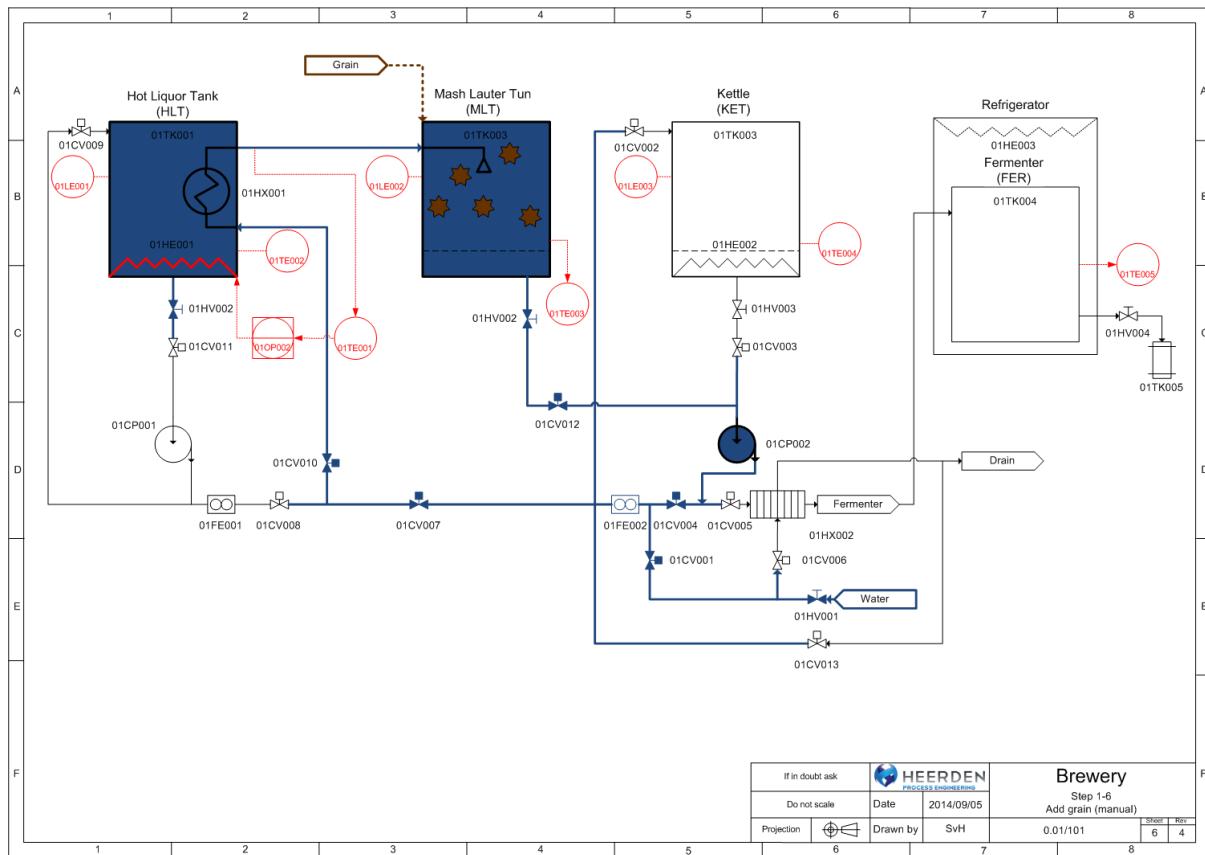


Figure 3.6: Add grain

3.1.7 Mash

Table 3.8: Step 1-7 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	65°C	Temperature 2	01TE002
KET element	01HE002	OFF	-	-
Pump 1	01CP001	ON	-	-
Pump 2	01CP002	OFF	-	-

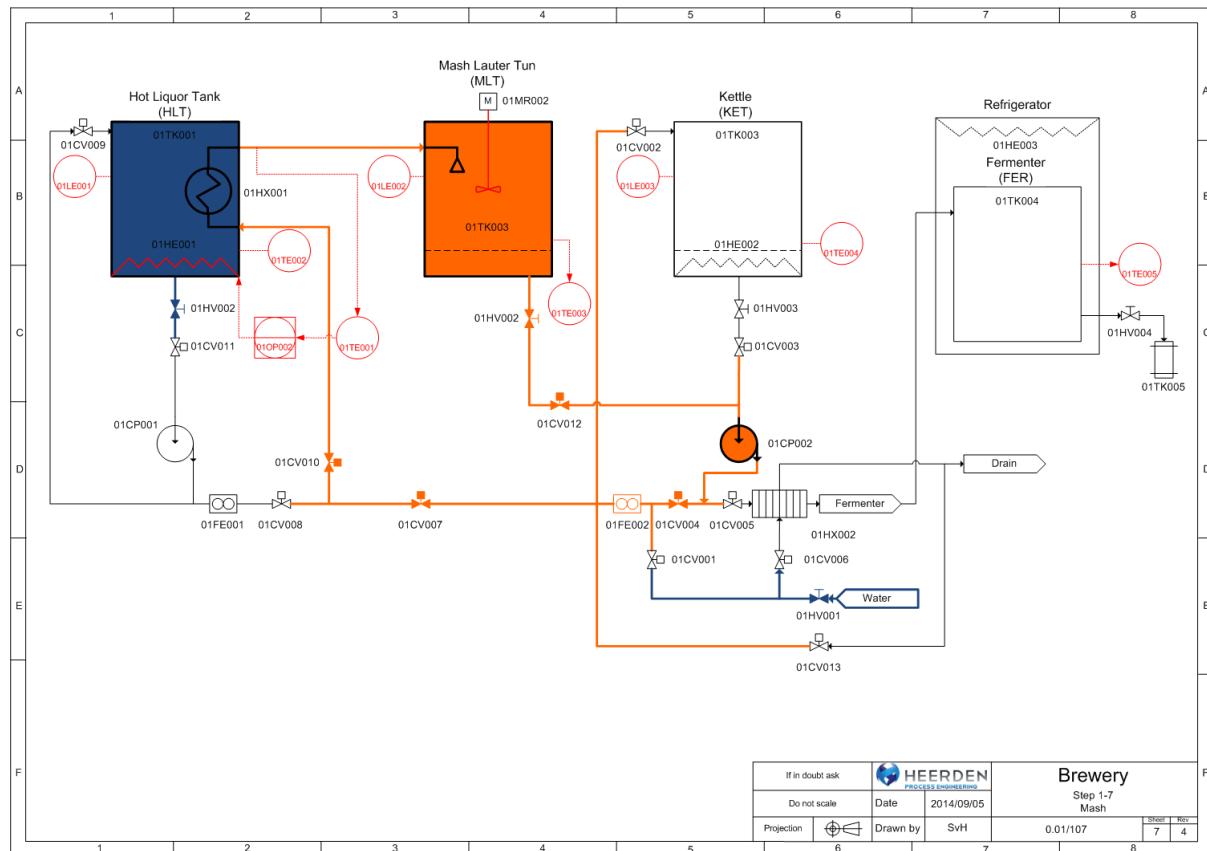


Figure 3.7: Mash

3.1.8 Mash out

Table 3.9: Step 1-8 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	75°C	Temperature 2	01TE002
KET element	01HE002	OFF	-	-
Pump 1	01CP001	ON	-	-
Pump 2	01CP002	OFF	-	-

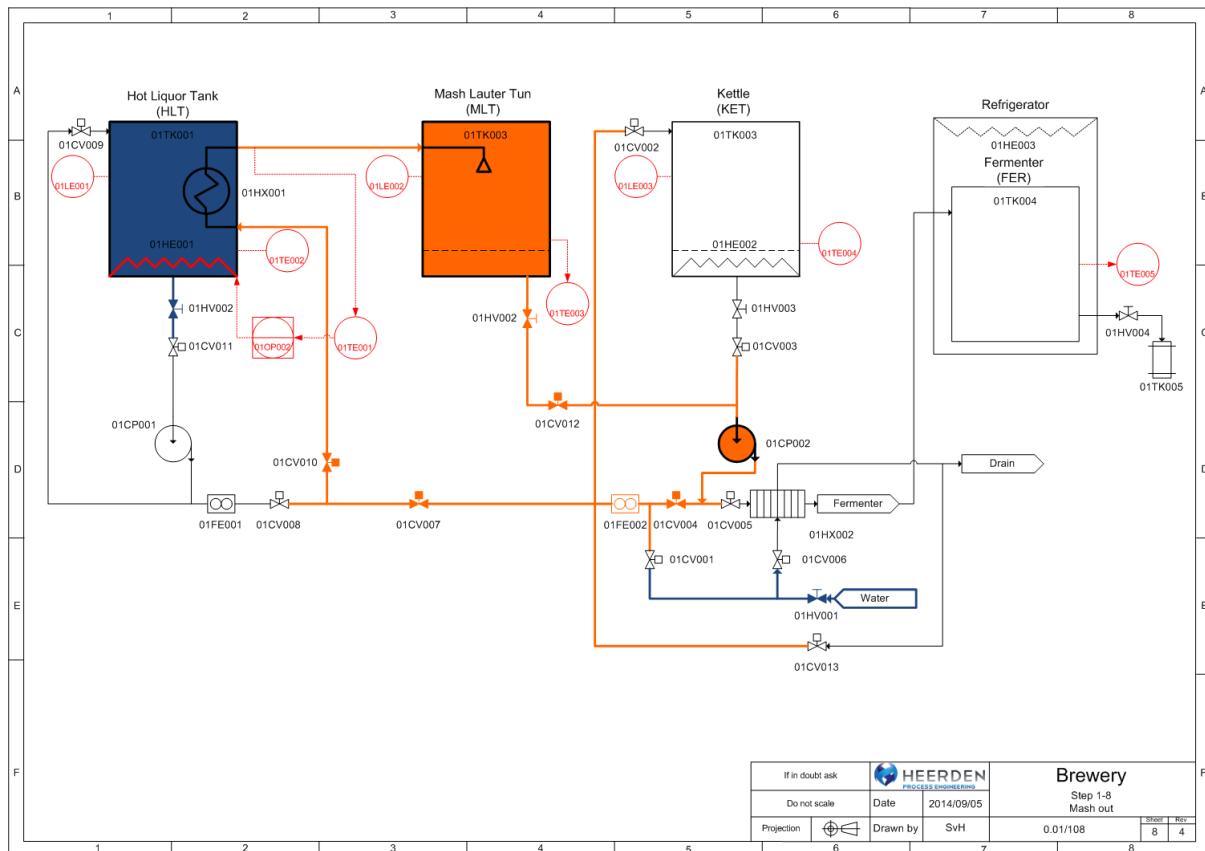


Figure 3.8: Mash out

3.1.9 Sparge

During this stage all the sugar that was extracted needs to transferred to the from the MLT to the KET. Heated water (75°C) from the HLT is pumped to MLT. The water in the MLT is needs to be maintained at a specific height.

A cascade control configuration is used to control the level, with a primary level (01LE002) loop and a secondary flow (01FE002) loop. The two loops will not interfere with each other because the primary loop is slower than the secondary loop, at least 4 times as suggested in the industry (Svrcek et al., 2000, 135).

Table 3.10: Step 1-9 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	75°C	Temperature 2	01TE002
KET element	01HE002	75°C	Temperature 4	01HE002
Pump 1	01CP001	ON	-	-
Pump 2	01CP002	ON	-	-
Valve 10	01CP010	100 mm	Level 2	01LE001

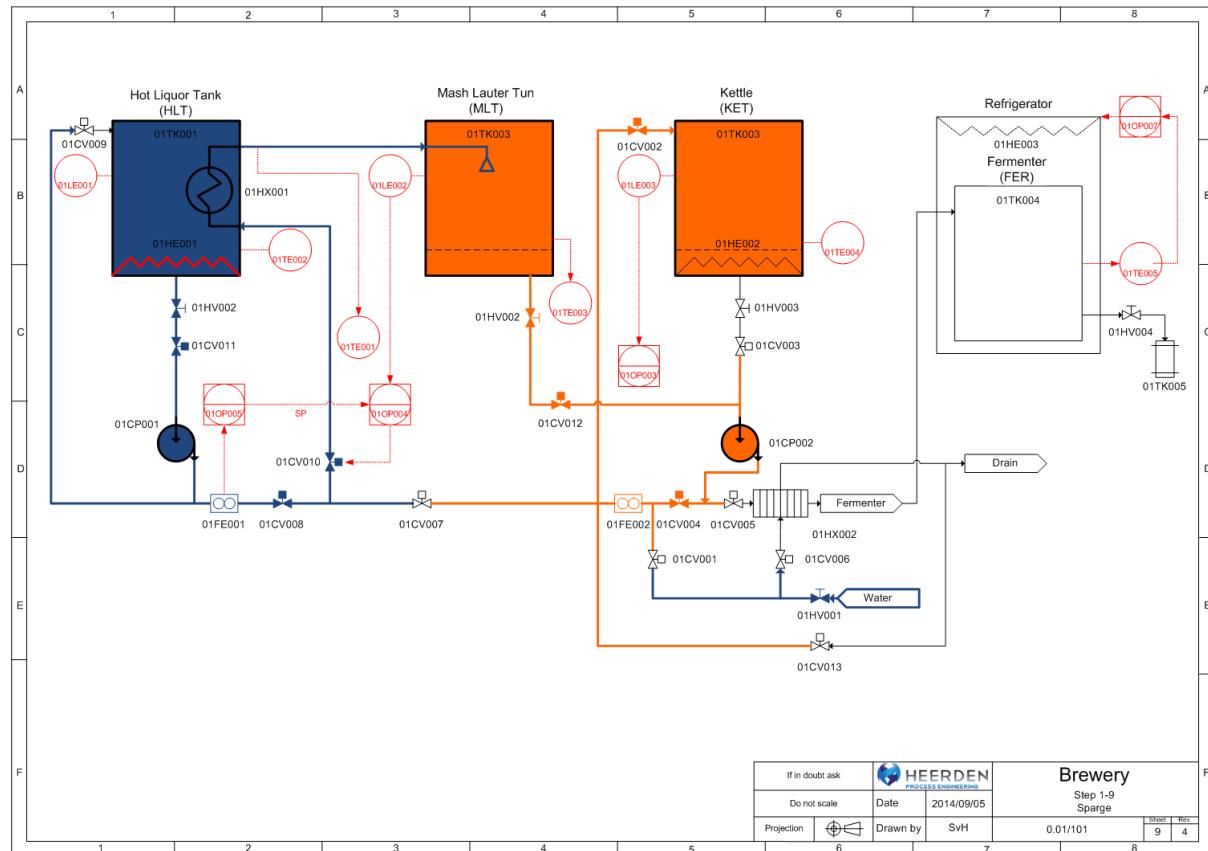


Figure 3.9: Sparge

3.1.10 Boil wort

Table 3.11: Step 1-10 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	BOIL	Temperature 3	01TE003
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-
Valve 10	01CP010	100 mm	Level 2	01LE001

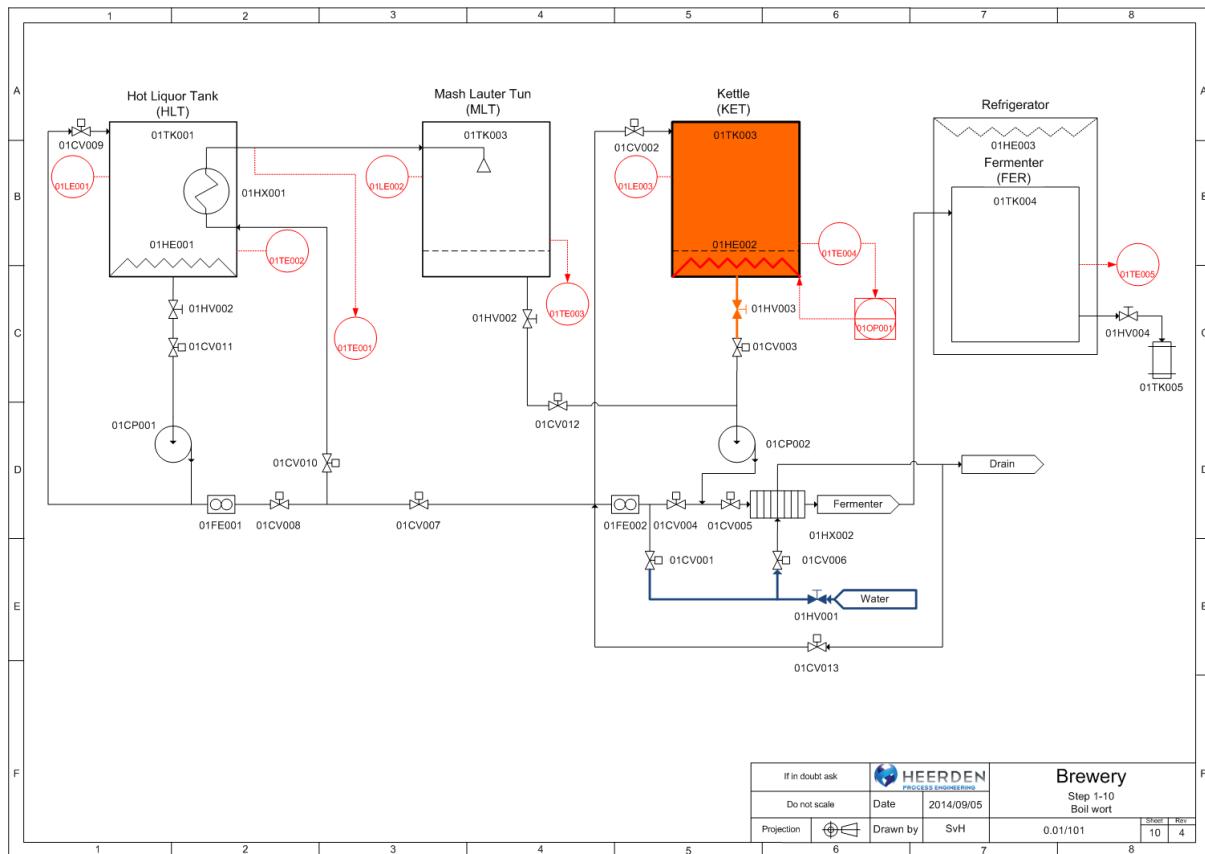


Figure 3.10: Boil wort

3.1.11 Add hops

Table 3.12: Step 1-11 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	BOIL	Temperature 3	01TE003
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	OFF	-	-
Valve 10	01CP010	100 mm	Level 2	01LE001

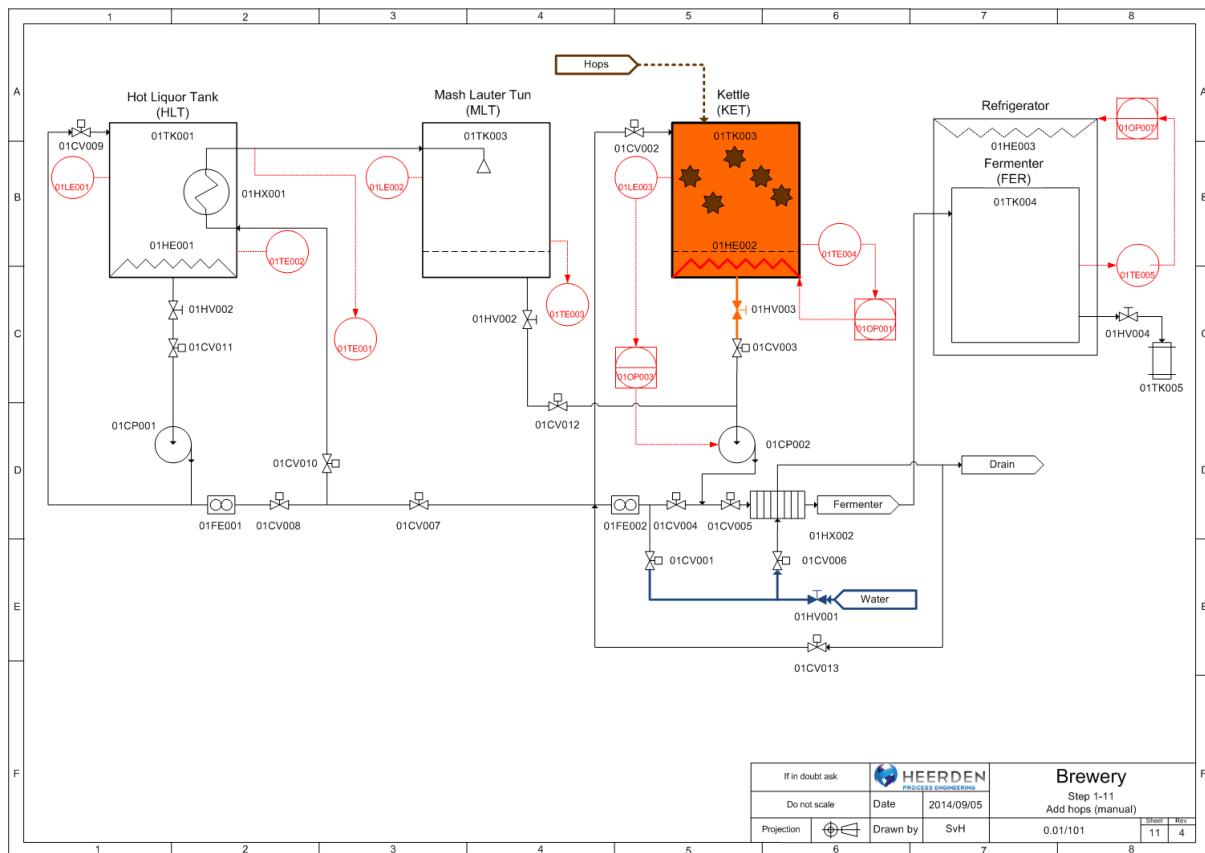


Figure 3.11: Fill FER with wort

3.1.12 Chill wort and fill FER

Table 3.13: Step 1-12 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
HLT element	01HE001	OFF	-	-
KET element	01HE002	OFF	-	-
Pump 1	01CP001	OFF	-	-
Pump 2	01CP002	ON	-	-

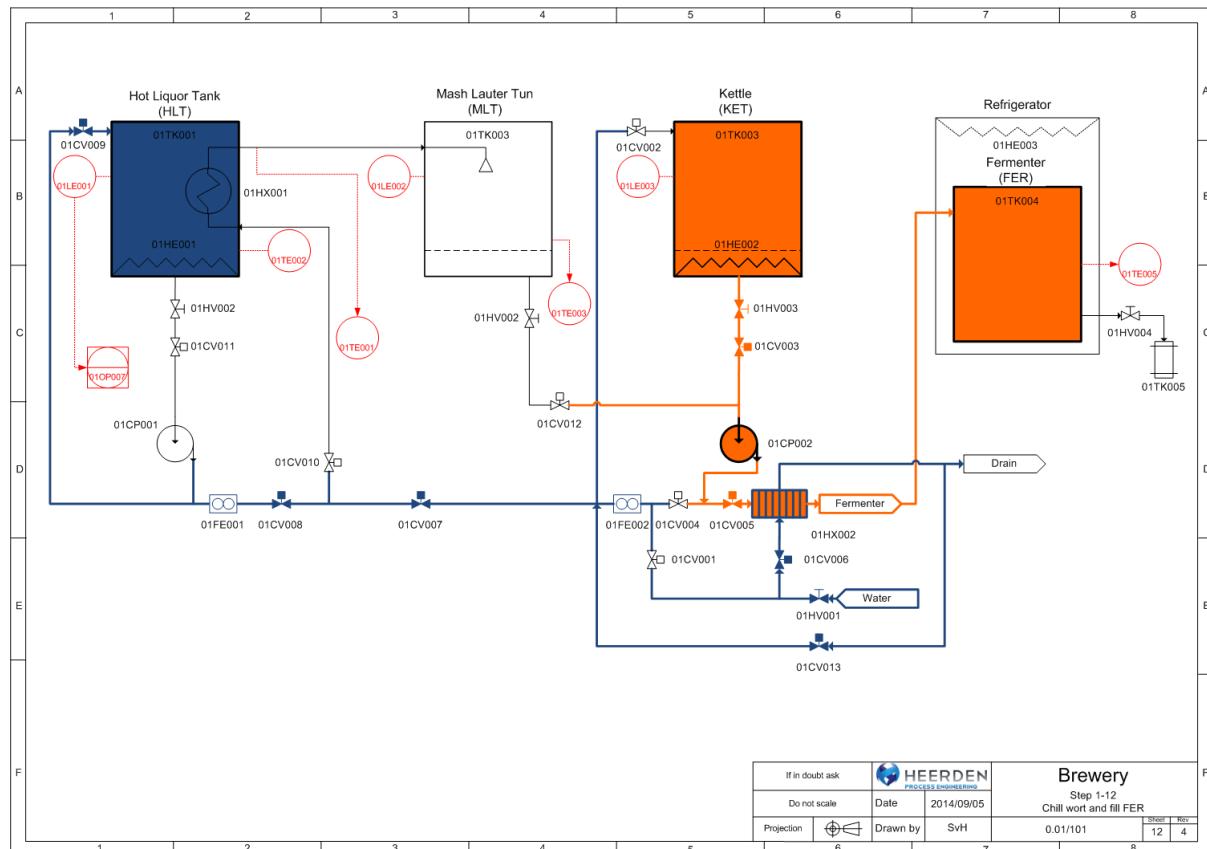


Figure 3.12: Chill wort and fill FER

3.2 Fermentation

Five process steps are required to ferment the beer in the FER:

1. Cool wort
2. Pitch yeast*
3. Control temperature
4. Add priming sugar*
5. Bottle beer*

3.2.1 Cool wort

Table 3.14: Step 2-1 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
FER element	01HE001	OFF	Temperature 6	20°C

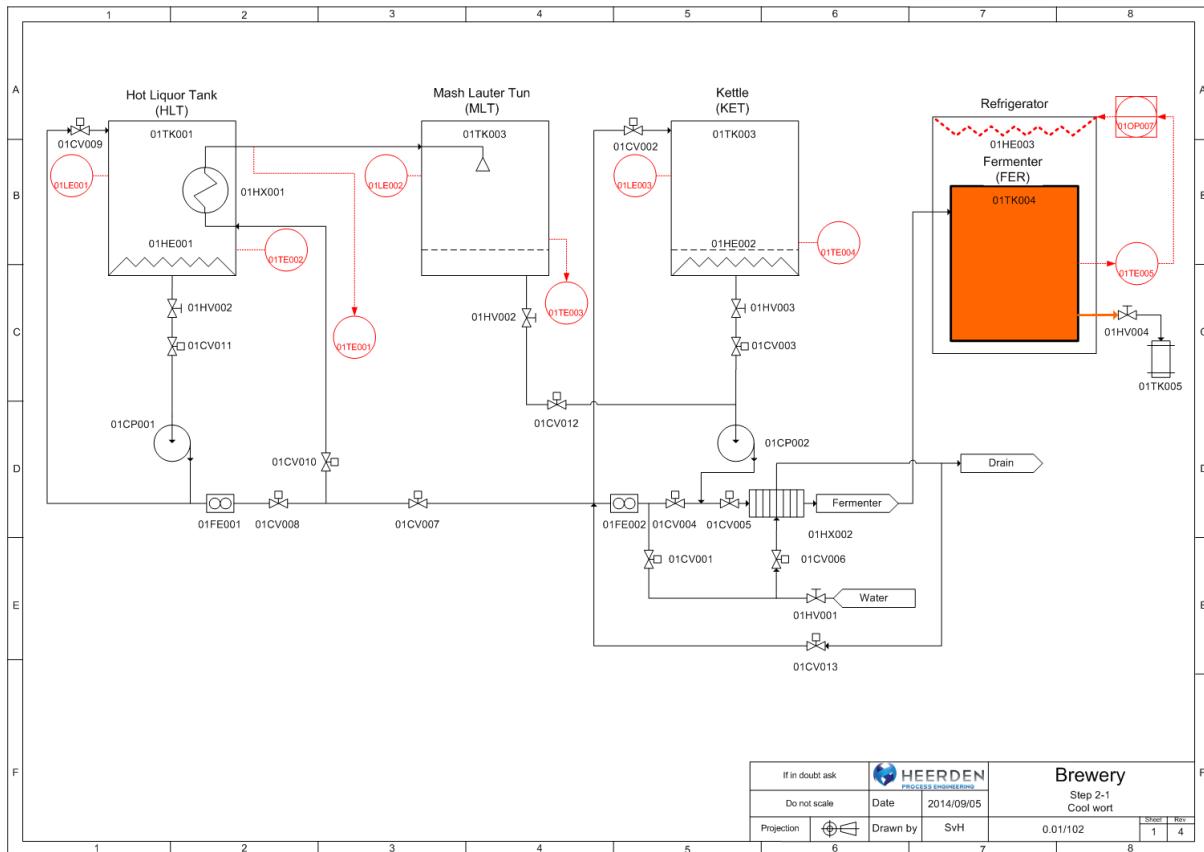


Figure 3.13: Cool wort

3.2.2 Pitch yeast

Table 3.15: Step 2-2 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
FER element	01HE001	20°C	Temperature 6	01TE006

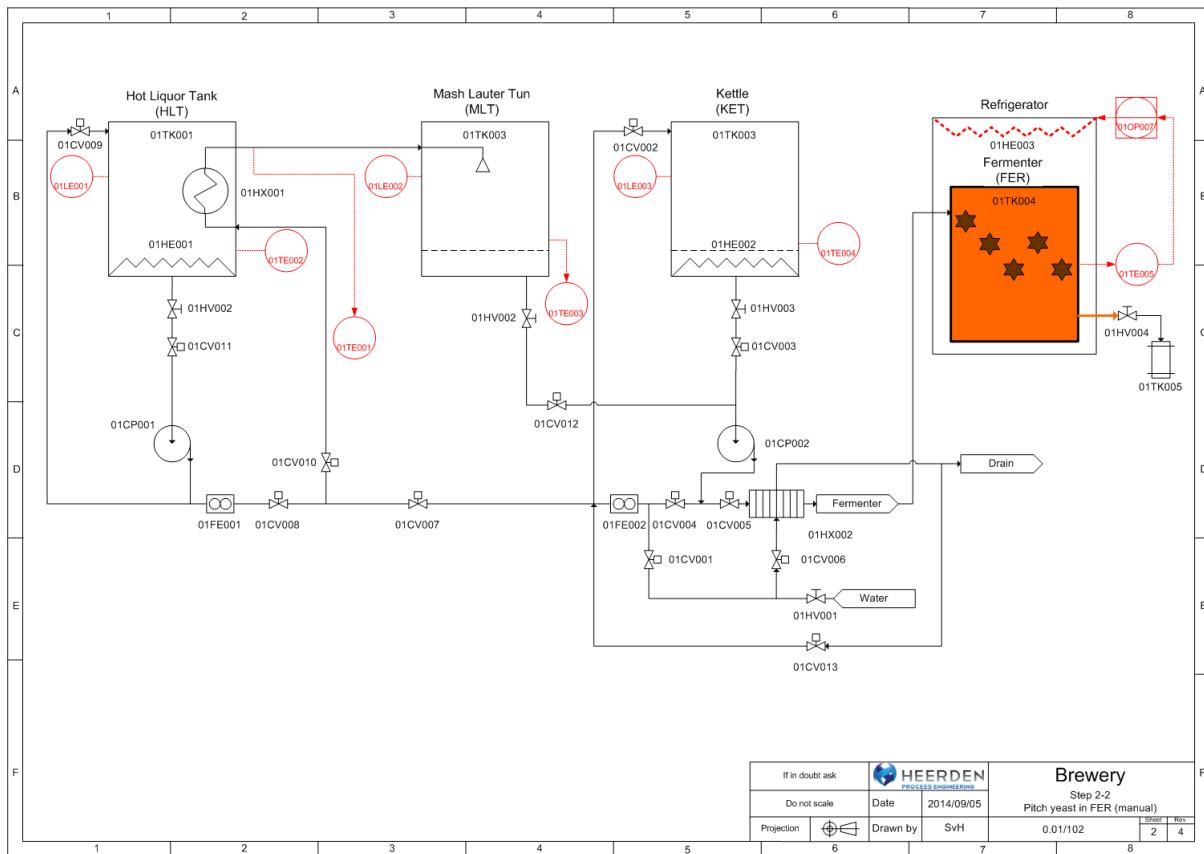


Figure 3.14: Pitch yeast

3.2.3 Control temperature

Table 3.16: Step 2-3 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
FER element	01HE001	20°C	Temperature 6	01TE006

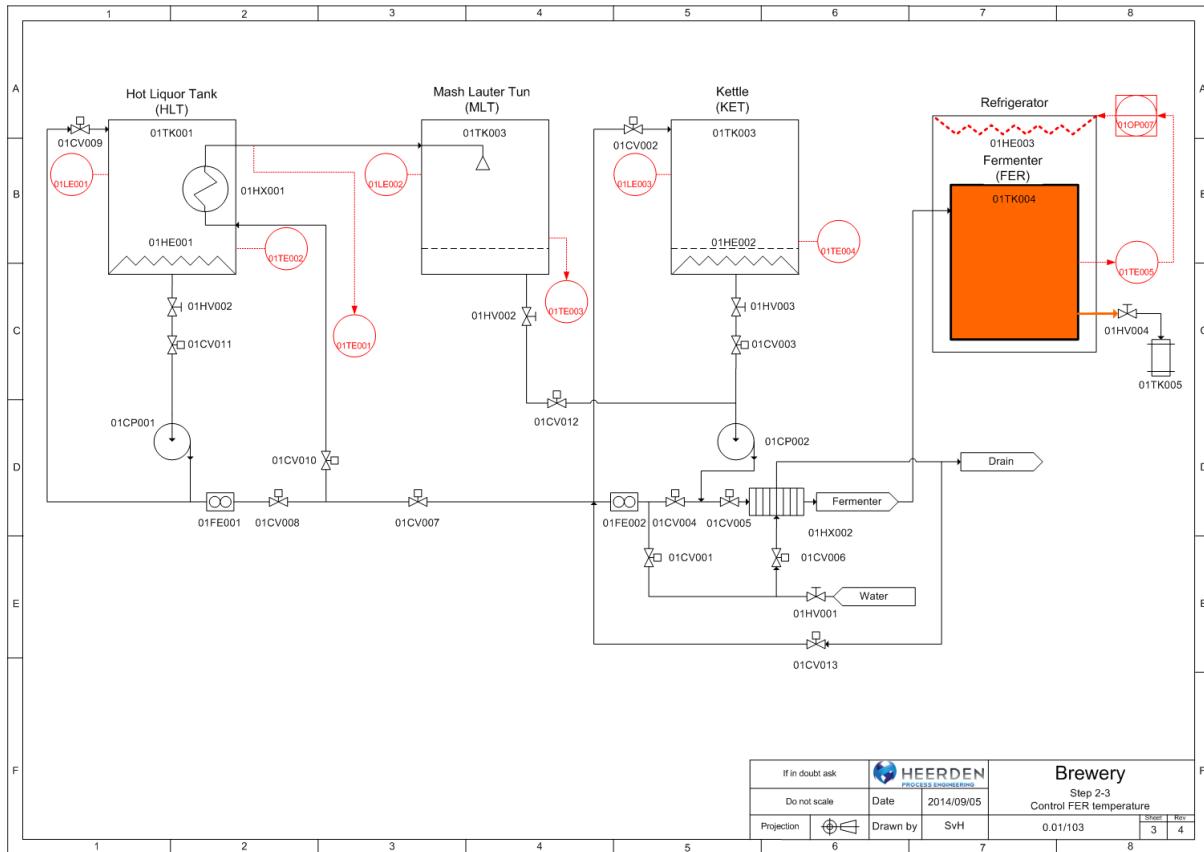


Figure 3.15: Control temperature

3.2.4 Add priming sugar

Table 3.17: Step 2-4 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
FER element	01HE001	20°C	Temperature 6	01TE006

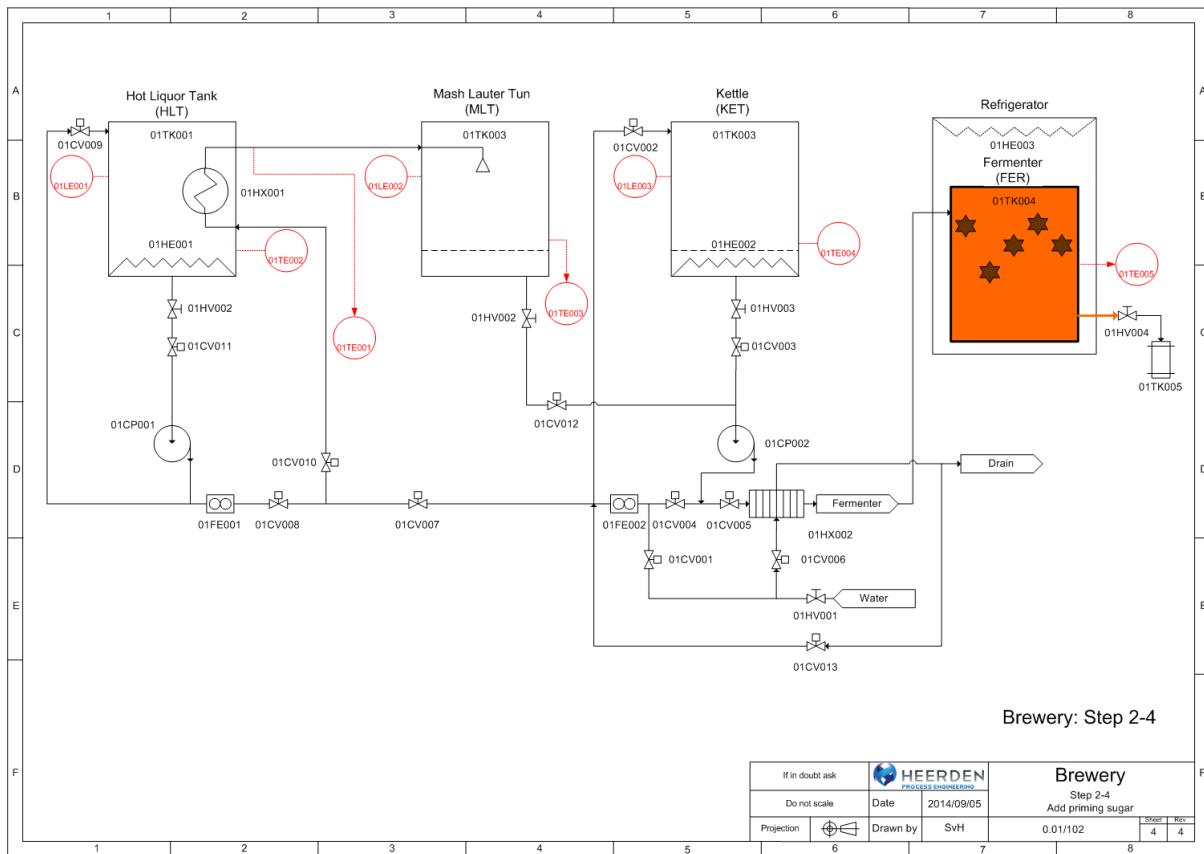


Figure 3.16: Add priming sugar

3.2.5 Bottle beer

Table 3.18: Step 2-5 process conditions

Control variable	Tag	Set point/function	Process variable	Tag
FER element	01HE001	20°C	Temperature 6	01TE006

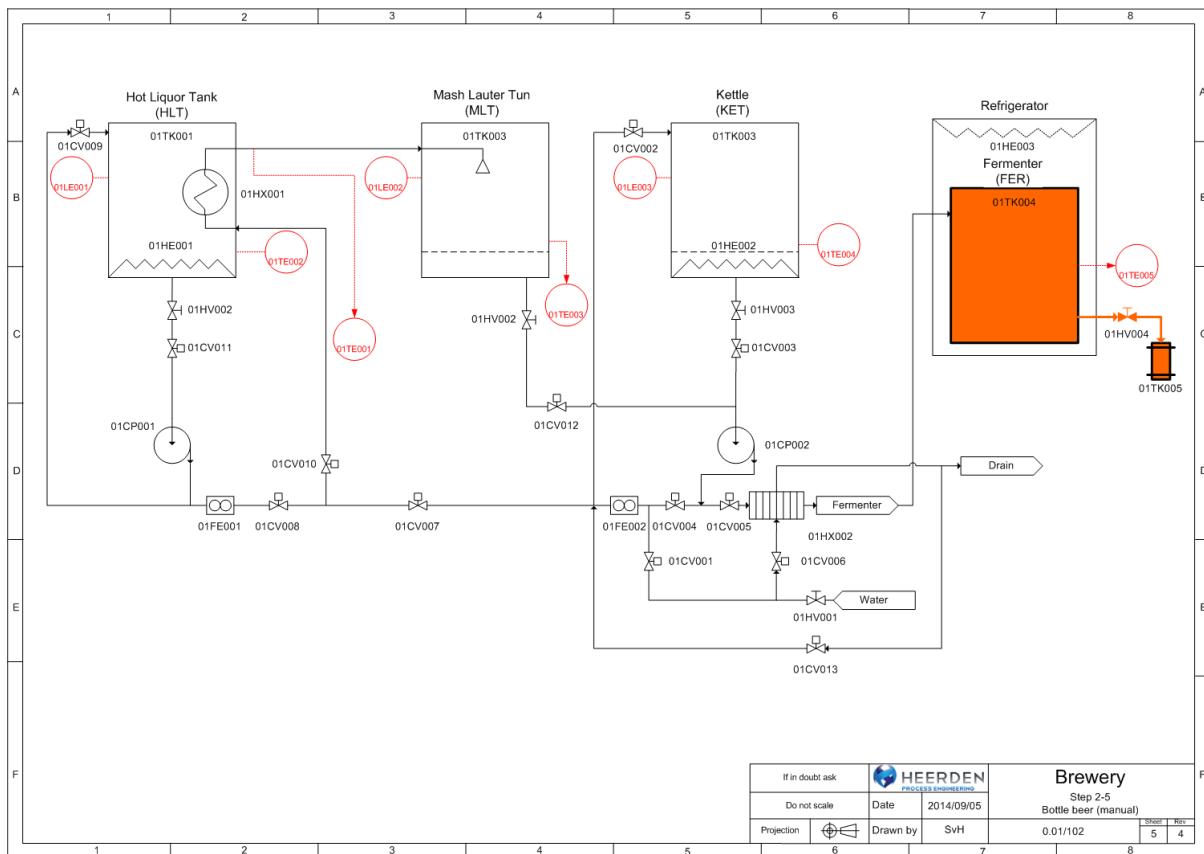


Figure 3.17: Bottle beer

3.3 CIP

At the end of the brewing process, the process equipment needs to be cleaned. This ensures hygienic and sterile conditions for the next brew. An automatic strategy called CIP will be used.

1. Add CIP solution to HLT
2. CIP for HLT section
3. Fill MLT with CIP solution
4. CIP for MLT section
5. Fill KET with CIP solution from HLT
6. Fill KET with CIP solution from MLT
7. Reconfigure HX and drain piping
8. CIP for KET section
9. CIP drain
10. Open cold water valve
11. Fill HLT with water and restart sequence

A summary of all these processes is given in Table 3.19.

Table 3.19: Step 3 clean in place process summary

Operation	Description	Mode	Time	Temperature (°C)				Level (mm)			Flow		Heat element	Pumps
				TE001	TE002	TE003	TE004	LE001	LE002	LE003	FE001	FE002		
3-1	Add CIP solution to HLT	Manual	Control panel	NR	NR	NR	NR	MR	NR	NR	NR	NR	C	C
3-2	CIP for HLT section	Auto	5 min	NR	NR	NR	NR	MR	NR	NR	NR	NR	C	O
3-3	Fill MLT with CIP solution	Auto	LE002	NR	NR	NR	NR	MR	MR	NR	NR	NR	C	C
3-4	CIP for MLT section	Auto	5 min	NR	NR	NR	NR	MR	MR	NR	NR	NR	C	C
3-5	Fill KET with CIP solution from HLT	Auto	LE001	NR	NR	NR	NR	MR	MR	MR	NR	NR	C	O
3-6	Fill KET with CIP solution from MLT	Auto	LE003	NR	NR	NR	NR	NR	MR	MR	NR	NR	C	C
3-7	Reconfigure HX and drain piping	Auto	Control panel	NR	NR	NR	NR	NR	MR	MR	NR	NR	C	C
3-8	CIP for KET section	Auto	5 min	NR	NR	NR	NR	MR	MR	MR	NR	NR	C	C
3-9	CIP drain	Auto	LE002 & LE003	NR	NR	NR	NR	NR	MR	MR	NR	NR	C	O
3-10	Open cold water valve	Manual	Control panel	NR	NR	NR	NR	MR	NR	NR	NR	NR	C	C
3-11	Fill HLT with water and restart sequence	Auto	LE001	NR	NR	NR	NR	MR	NR	NR	NR	NR	C	C

Operation	Description	Mode	Time	Valves												Heat element	Pumps
				CV001	CV002	CV003	CV004	CV005	CV006	CV007	CV008	CV009	CV010	CV011	CV012	CV013	HV001
3-1	Add CIP solution to HLT	Manual	Control panel	C	C	C	C	C	C	C	C	C	C	C	C	C	C
3-2	CIP for HLT section	Auto	5 min	C	C	C	C	C	C	C	M	O	C	O	C	C	C
3-3	Fill MLT with CIP solution	Auto	LE002	C	C	C	C	C	C	C	O	C	C	O	C	C	C
3-4	CIP for MLT section	Auto	5 min	C	O	C	C	C	C	C	O	C	C	O	C	C	C
3-5	Fill KET with CIP solution from HLT	Auto	LE001	C	C	C	O	C	C	C	O	C	C	O	C	C	C
3-6	Fill KET with CIP solution from MLT	Auto	LE003	C	O	C	C	O	C	C	C	C	C	O	C	C	C
3-7	Reconfigure HX and drain piping	Auto	Control panel	C	O	C	O	C	C	O	O	C	C	O	C	C	C
3-8	CIP for KET section	Auto	5 min	O	O	O	O	O	O	C	C	C	C	C	C	C	C
3-9	CIP drain	Auto	LE002 & LE003	C	C	O	O	C	C	C	C	C	C	O	O	C	C
3-10	Open cold water valve	Manual	Control panel	C	C	C	C	C	C	C	C	C	C	C	O	O	O
3-11	Fill HLT with water and restart sequence	Auto	LE001	O	C	C	C	C	C	O	O	O	C	C	C	O	O

Key	
[O]	Open/on
[C]	Closed/off
[M]	Modulated
[Value]	Setpoint
[MR]	Monitor
[NR]	Not Required

3.3.1 Add CIP solution to HLT

Bleach is an inexpensive solution. If it is used, it needs to be rinsed from the process in step 3-11.

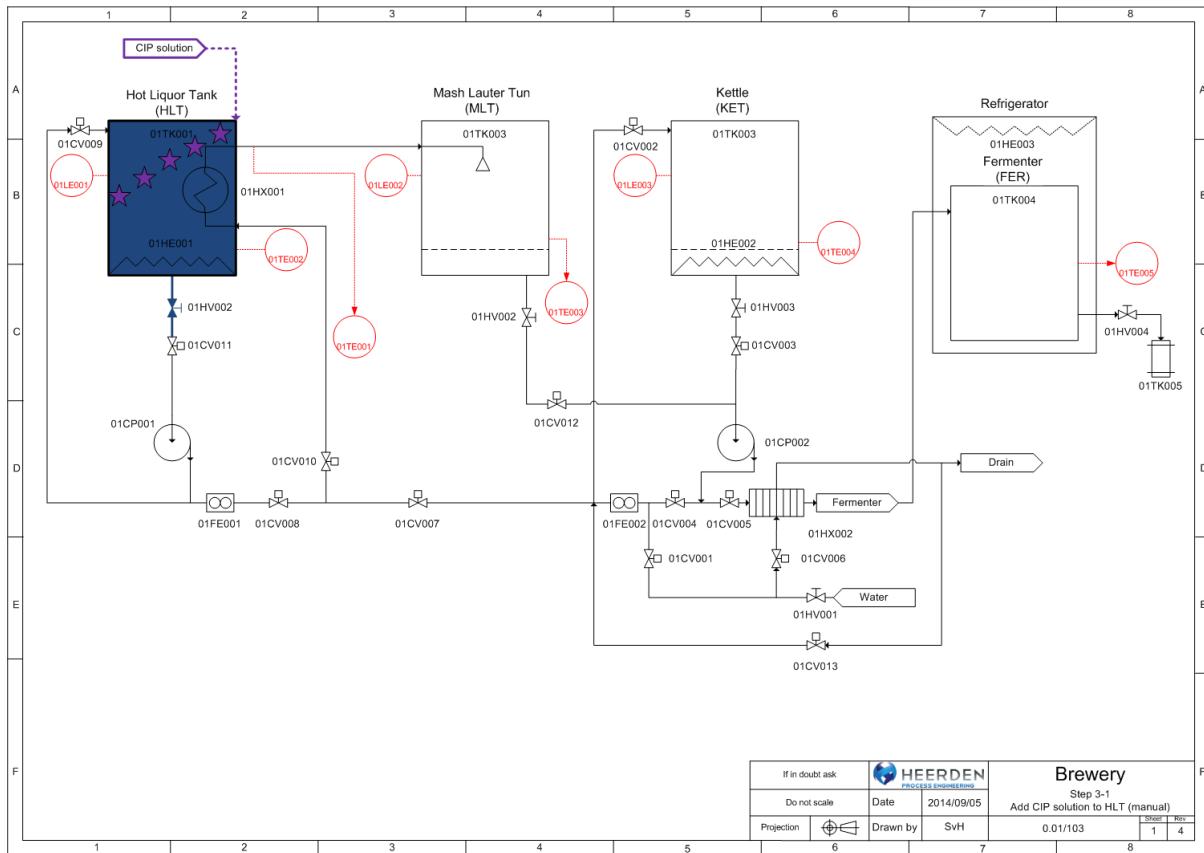


Figure 3.18: Add CIP solution to HLT

3.3.2 CIP for HLT section

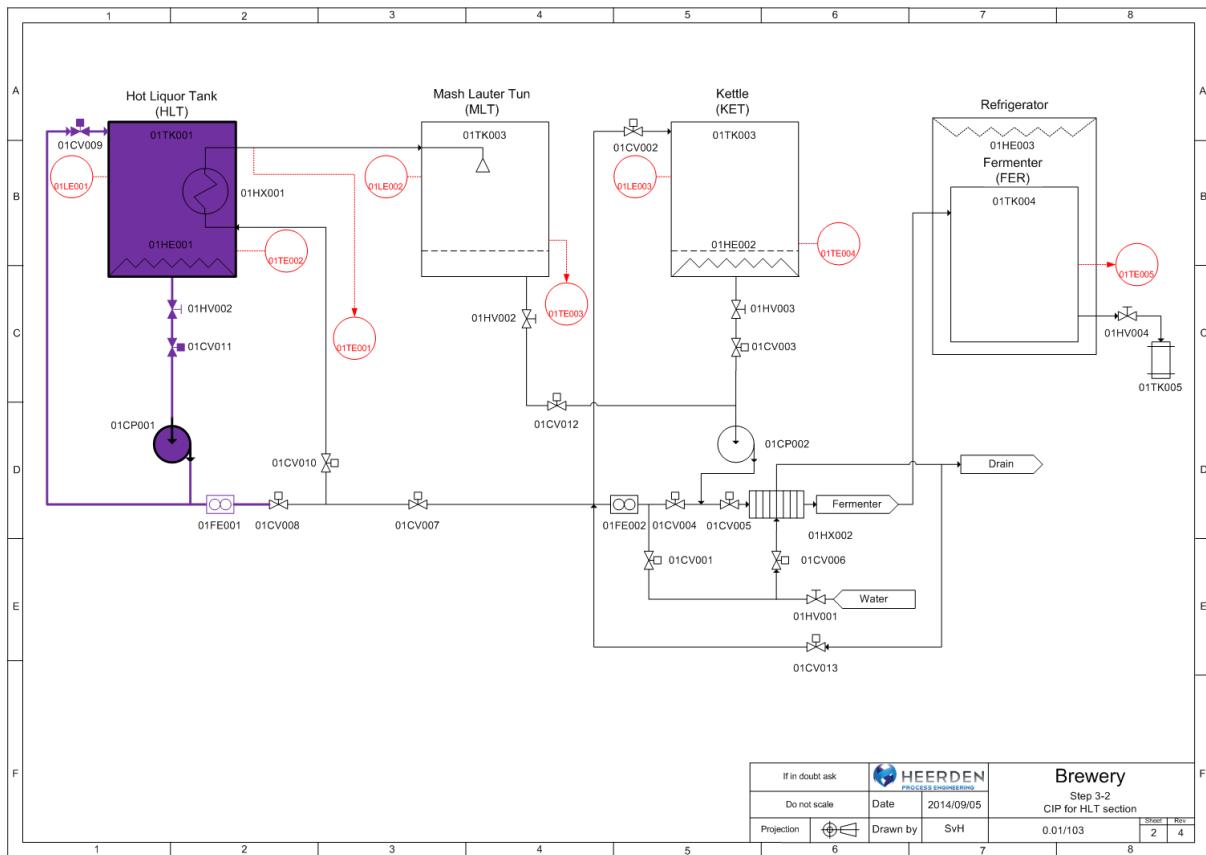


Figure 3.19: CIP for HLT section

3.3.3 Fill MLT with CIP solution

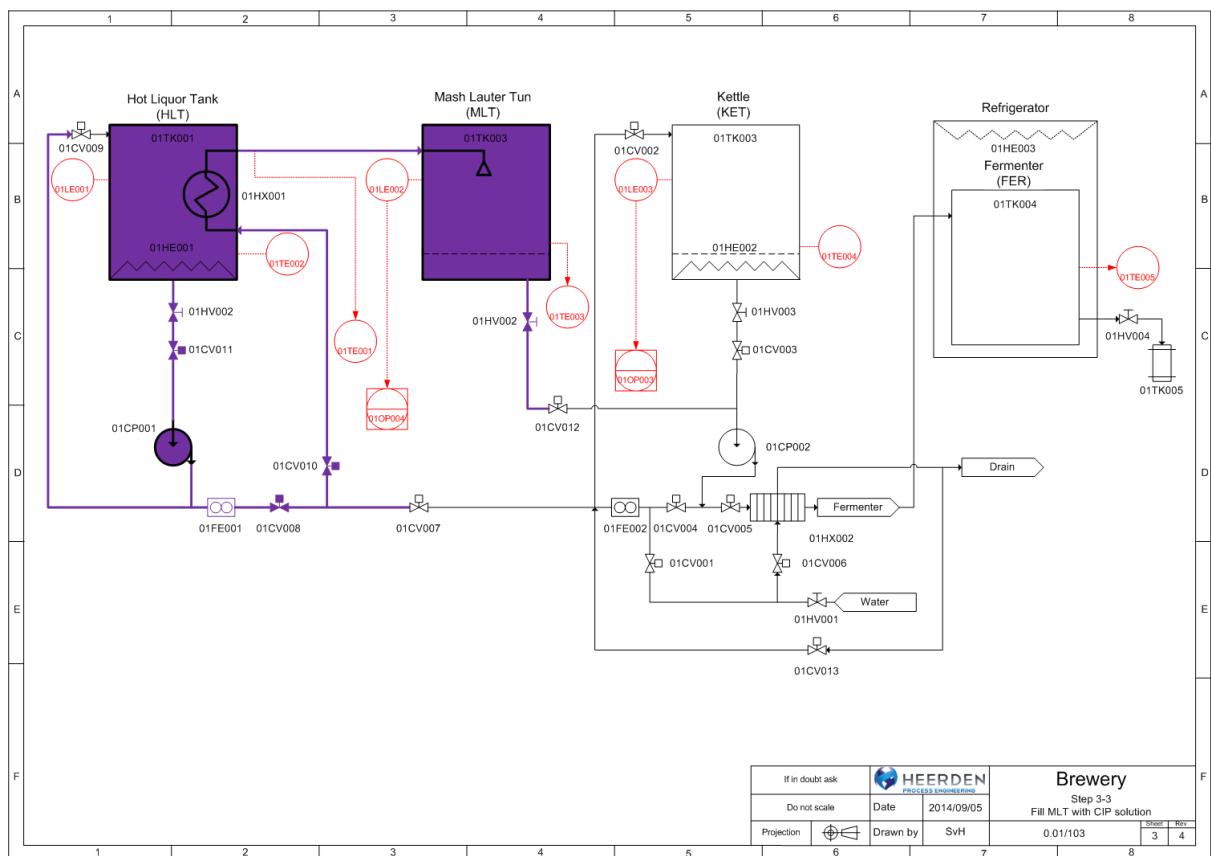


Figure 3.20: Fill MLT with CIP solution

3.3.4 CIP for MLT section

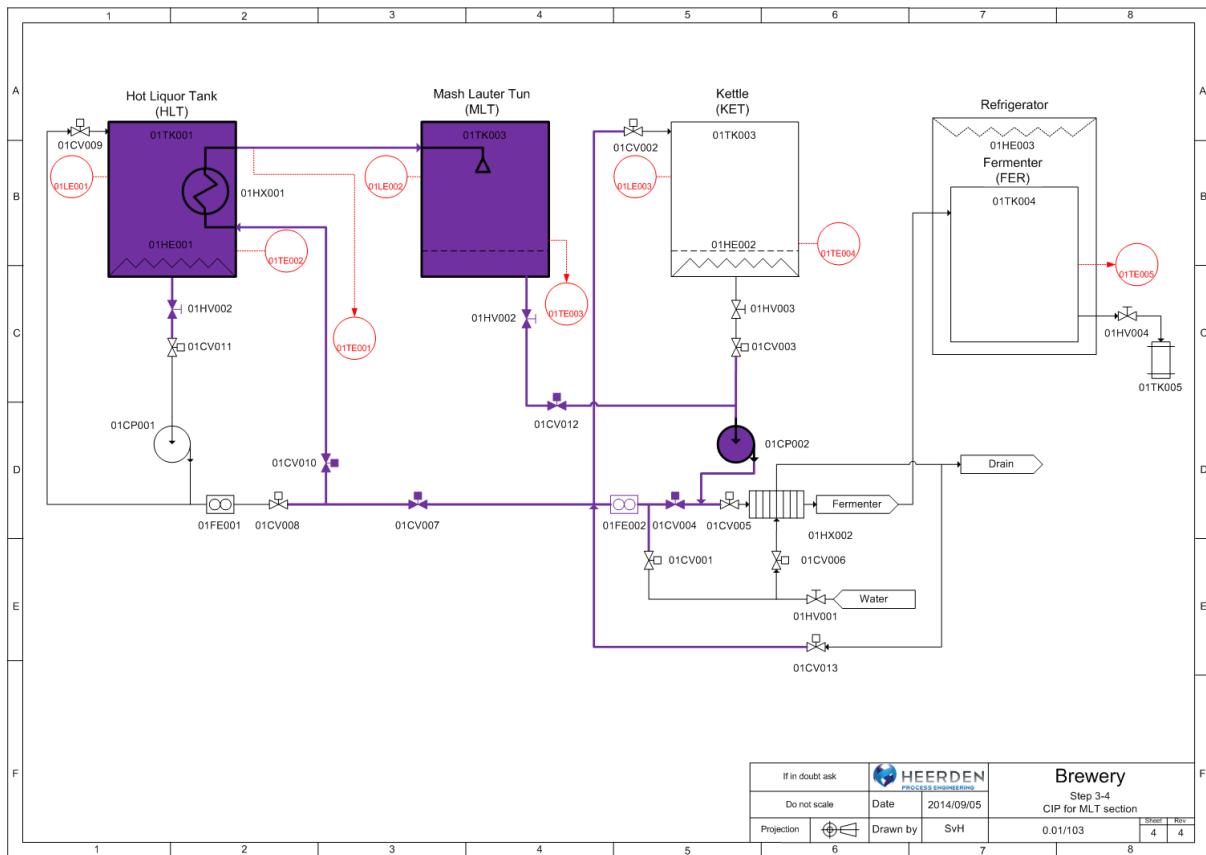


Figure 3.21: CIP for MLT section

3.3.5 Fill KET with CIP solution from HLT

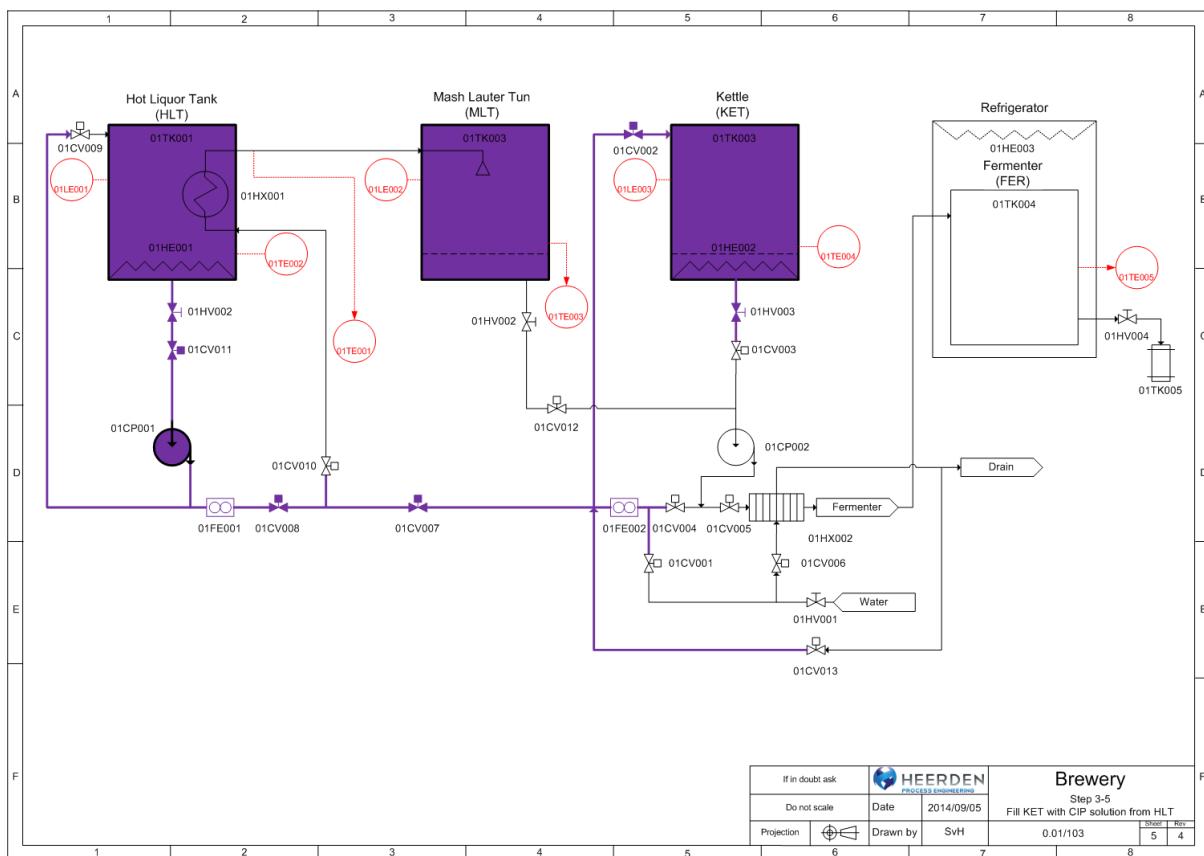


Figure 3.22: Fill KET with CIP solution from HLT

3.3.6 Fill KET with CIP solution from MLT

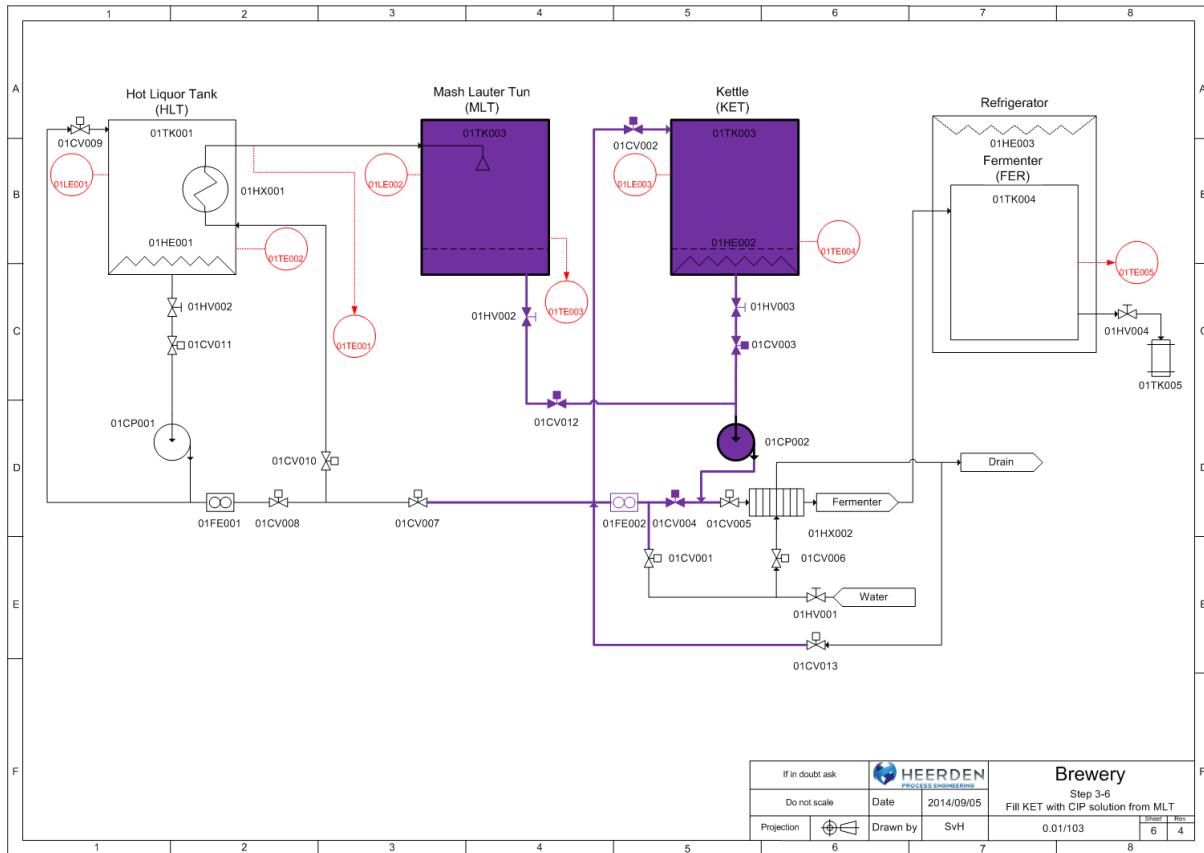


Figure 3.23: Fill KET with CIP solution from MLT

3.3.7 Reconfigure HX and drain piping

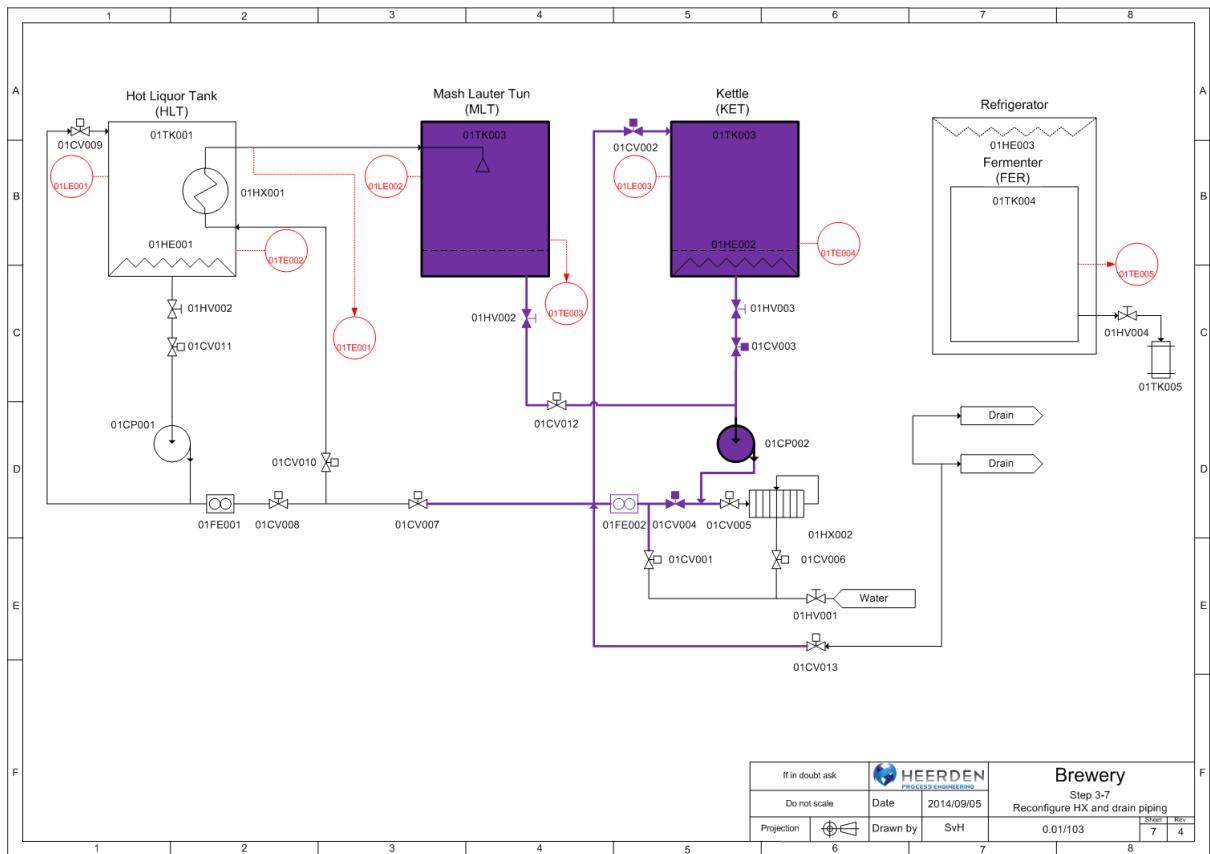


Figure 3.24: Reconfigure HX and drain piping

3.3.8 CIP for KET section

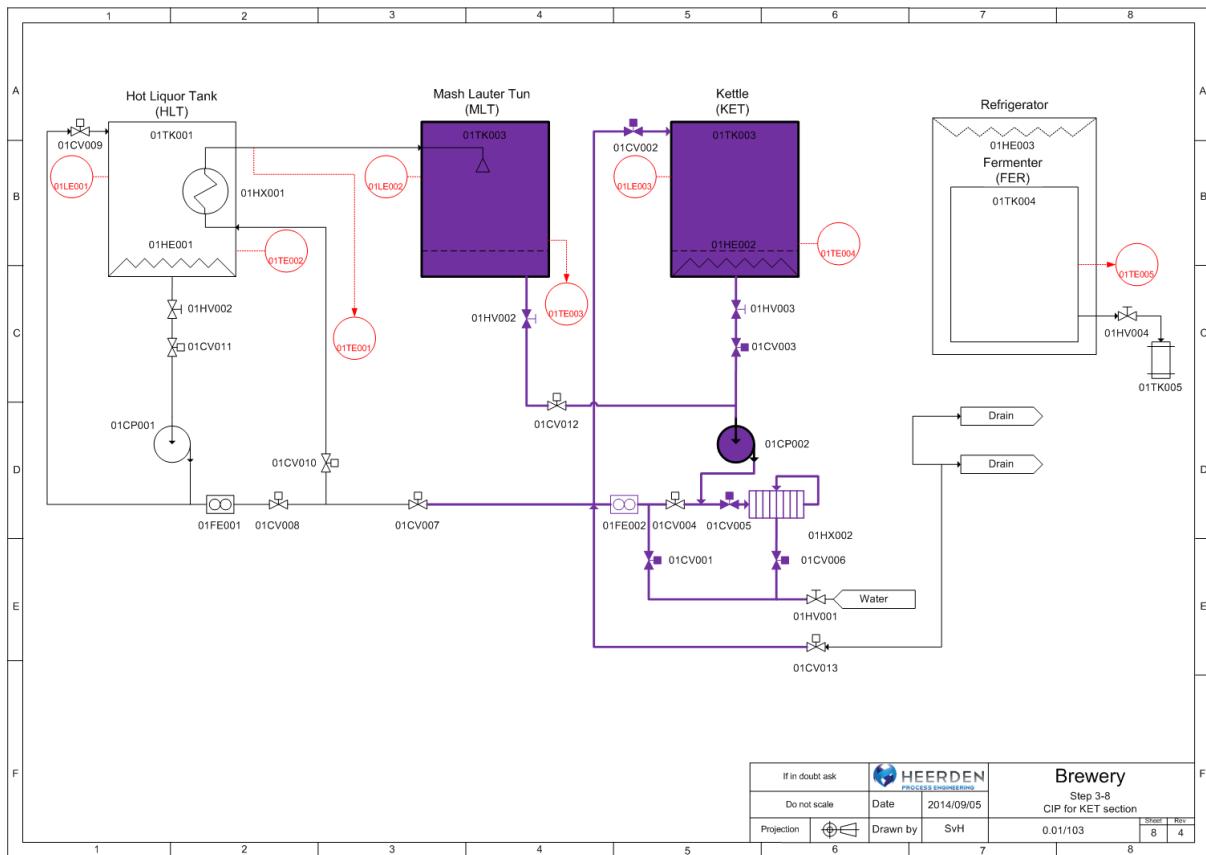


Figure 3.25: CIP for KET section

3.3.9 CIP drain

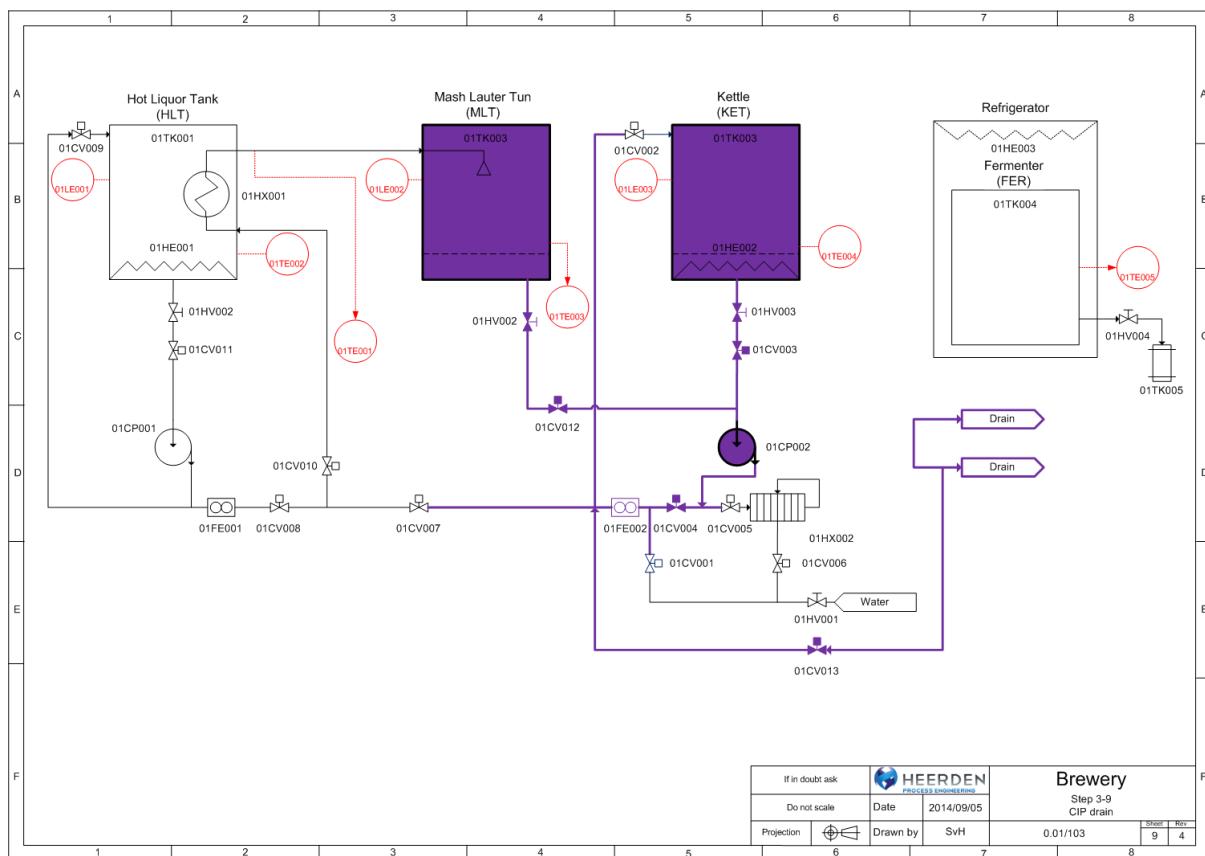


Figure 3.26: CIP drain

3.3.10 Open cold water

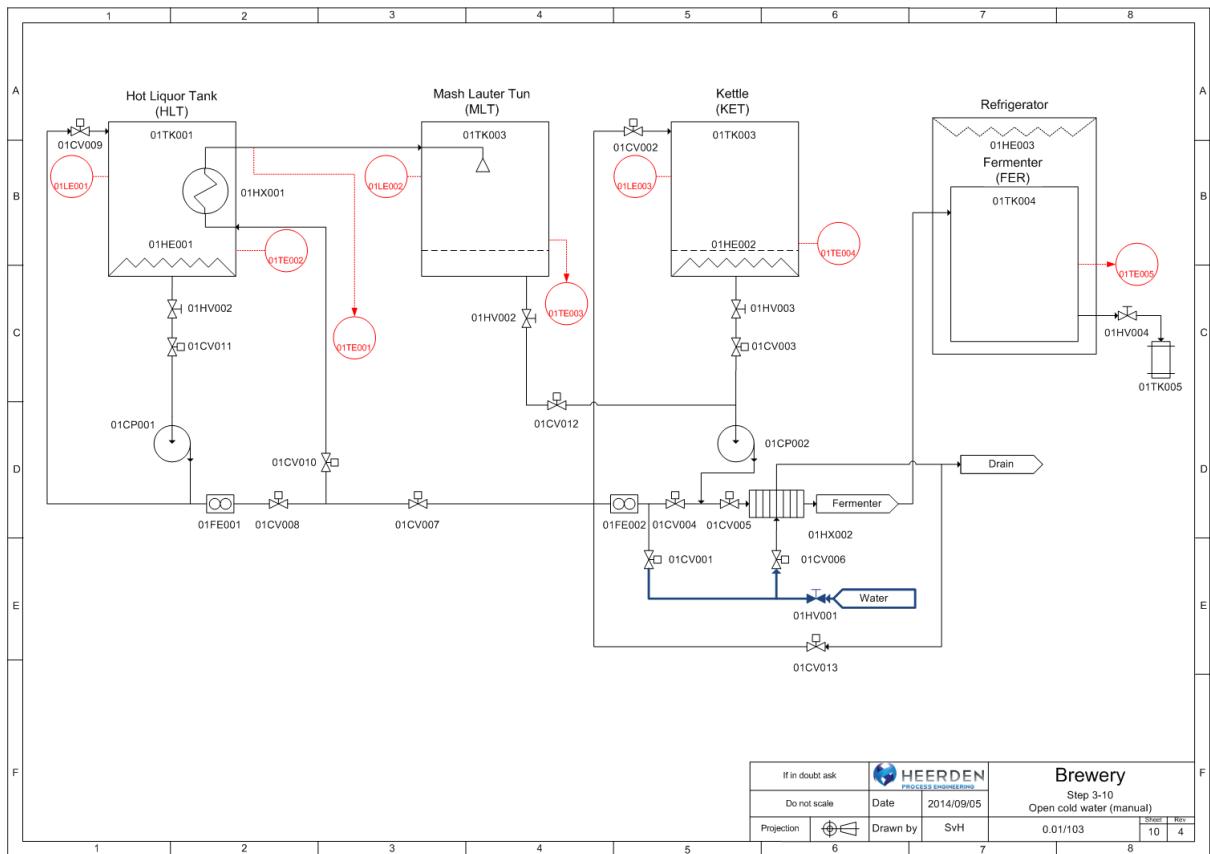


Figure 3.27: Open cold water

3.3.11 Fill HLT with water and restart sequence

Repeat the whole CIP process from step 3-2 to 3-9, with only water in the system.

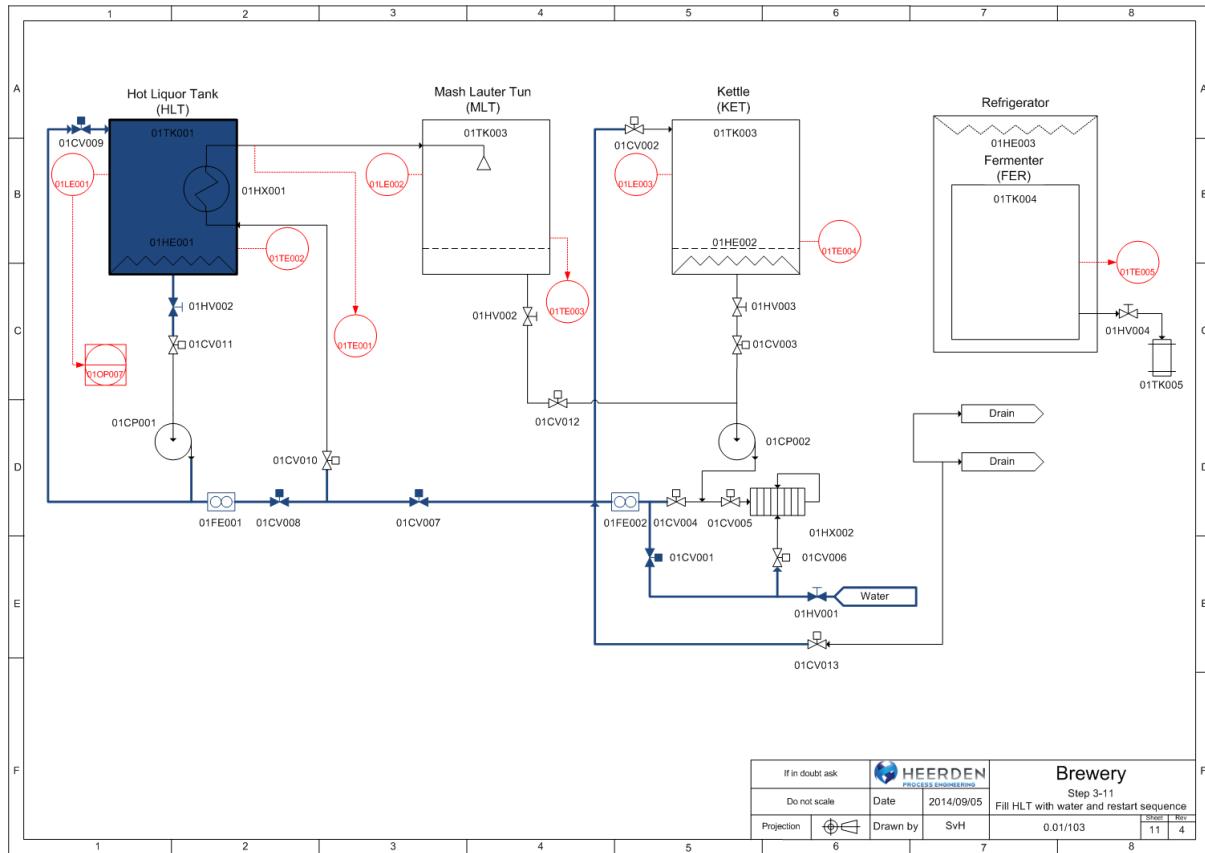


Figure 3.28: Fill HLT with water and restart sequence

Chapter 4

Mechanical design

In this chapter, diagrams and descriptions will be given of the mechanical equipment for the brewery.

4.1 Vessel and piping overview

An overview of the mechanical equipment is given in Figure 4.1.

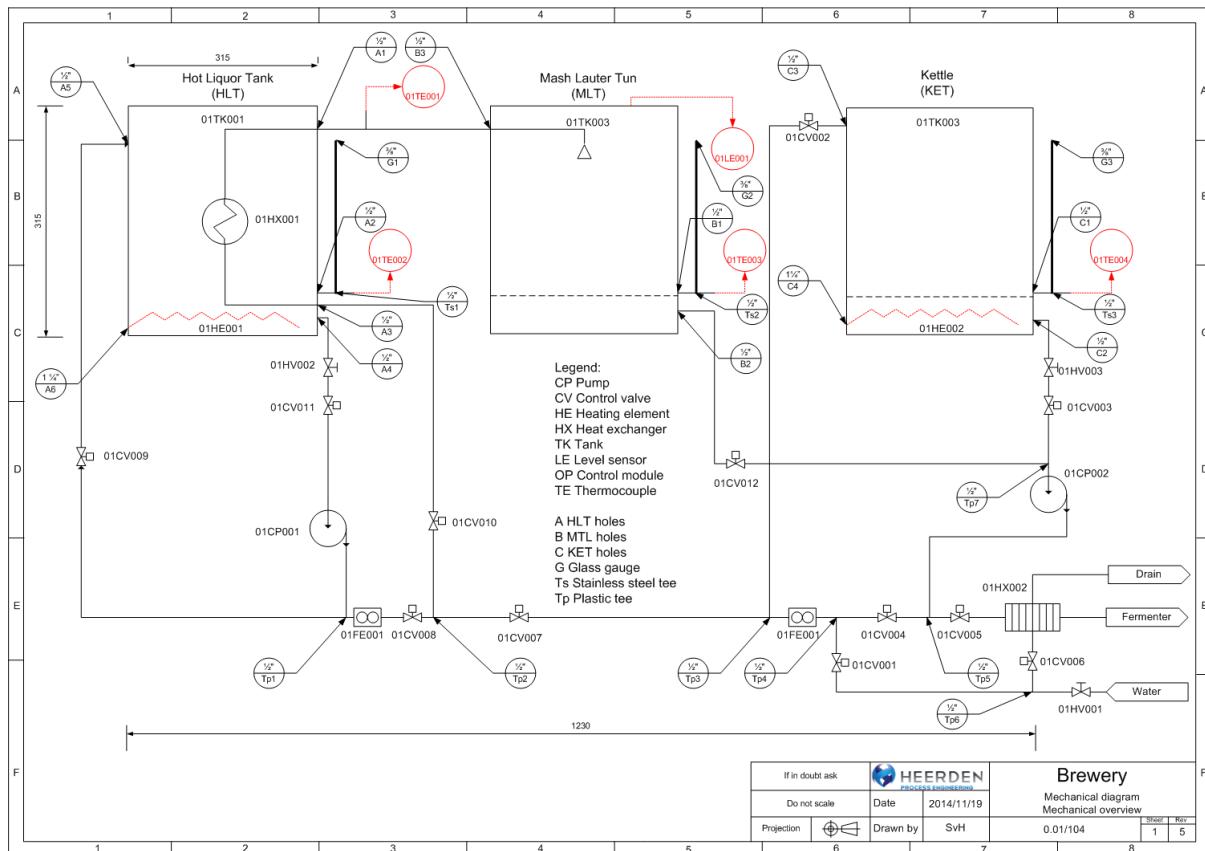


Figure 4.1: Vessel and piping

The first alternative for material of construction for the process vessels is High-density Polyethylene (HDPE). The material is very economical, and used by many home brewers,

but vessel supplier do not guarantee the operating temperatures for this process. In the food and beverage industry, Stainless Steel (SS) and silicon are the materials of choice used to maintain a food grade standard. Thus SS vessel will be used.

For a rigid process layout SS pipes are required, but the pipes and welding of the joint are costly. While the flow configuration is tested, plastic piping is used. Later the process will be upgraded to silicon piping.

Figure 4.1 gives the location and sizes of holes required in the three vessels. Various fittings will be connected in the holes.

Imperial dimensions is the industry standard for most equipment. All the equipment and instruments will have $\frac{1}{2}$ in (12.7 mm) threaded nozzles. 12 mm piping will however be used.

A single tier system will be used. This means that all the vessels are on the same level and pumps are required to transfer the process liquid. On a two or three tier system, gravity also facilitates the transfer of process liquids. The disadvantage of this approach is that the ergonomics of the system is poor, as the operator will need to step on top of a ladder to access the second or third level vessels.

4.2 Control valve assembly

Valve 01CV010 needs to be modulated to control the level of the MLT during the sparging step. Commercial control valves are however very expensive and a cost effective solution was therefore required. A normal ball valve is used and a motor is mounted on top of the valve, with an mounting part that was specially manufactured. An arm is inserted on the motor's rotar, which is fastened to the valve arm.

The feedback for the valve positioning is obtained with a cascade control configuration from flow meter 01FE001. The details of the flow meter and motor will be discussed in section 5.4.1 and 5.4.5 respectively.

The torque required to turn the ball valve is 488 N m. Two type of control motors is considered, a servo and a stepper motor. Servo motors are not cost effective at a high torque rating, but gears can however be used to increase their rating. This will add additional cost to the valve assembly that is already being custom designed. With all the options weighed a stepper motor with a holding torque of 770 N m was selected. It was over designed to accommodate any issues during testing and operation. The mechanical details of the valve assembly can be seen in Figure 4.2.

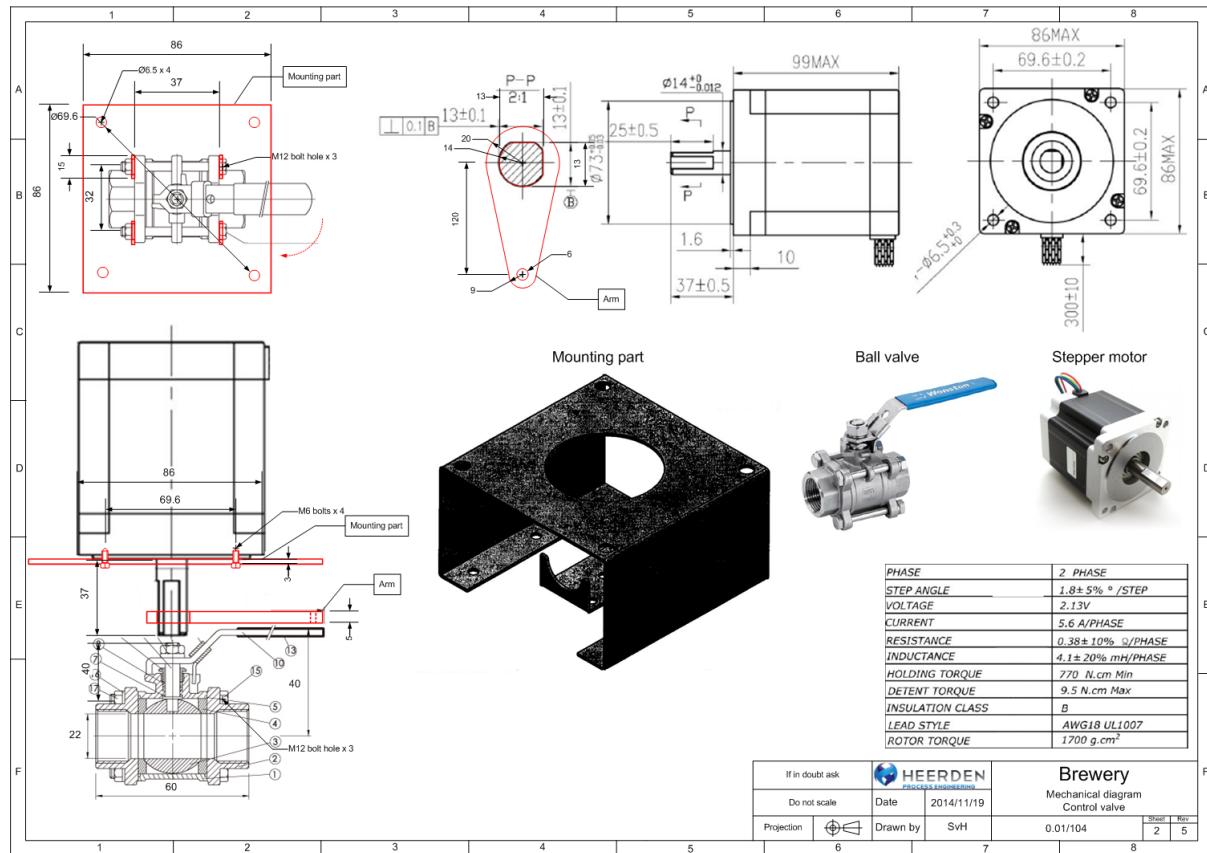


Figure 4.2: Control valve

4.3 Probes

Two types of temperature probes was considered; the PT100 analog sensor with threaded connection and the DS18B20 digital sensor which is enclosed in a water proof thermowell. The electrical details of these sensors will be discussed in section 5.4.2.

Weighing the mechanical and electrical implication of these probes, it was decided to use the DS18B20 sensor. A standard $\frac{1}{2}$ in to $\frac{3}{8}$ in fitting (UMC-0608N) was used to screw into a tee piece that is either connected to the tanks or a line. The diameter of the DS18B20 was only 5 mm and the probe enclosure was specially manufactured to fit in the UMC-0608N fitting.

To optimise space on the vessels, the level gauge and temperature probe was connected to one tee piece. The mechanical details and assembly order of the probes can be seen in Figure 4.3.

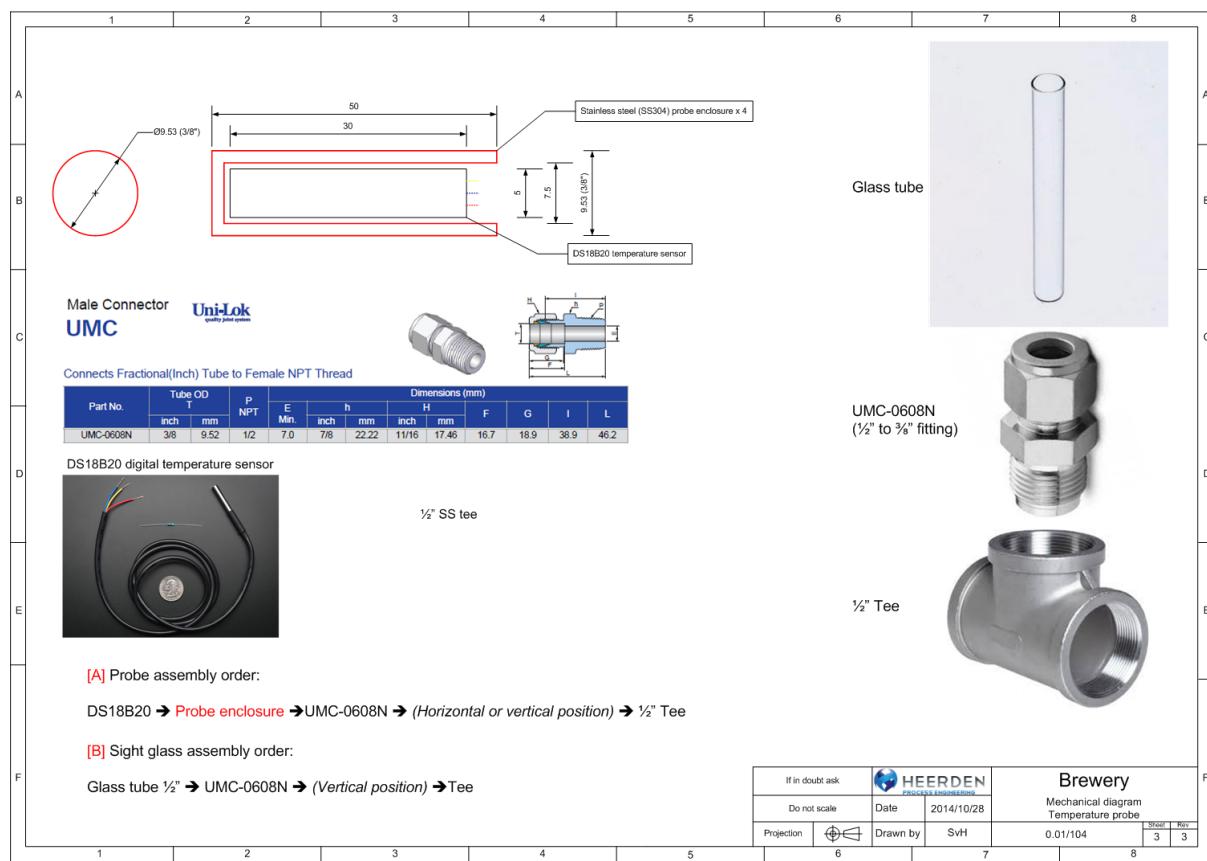


Figure 4.3: Temperature probe

4.4 Vessel fittings

The use of vessel fittings is not an absolute requirement. The fittings allow all the piping and heating elements to be firmly fixed. It also reduce the changes of spillage and contamination in the process.

The mechanical details (pictures) and assembly order of the fittings are given in Figure 4.4.

If an electrical urn is used, the heating element and exit valve is already in place. In the testing phase of this study, this design will be used.

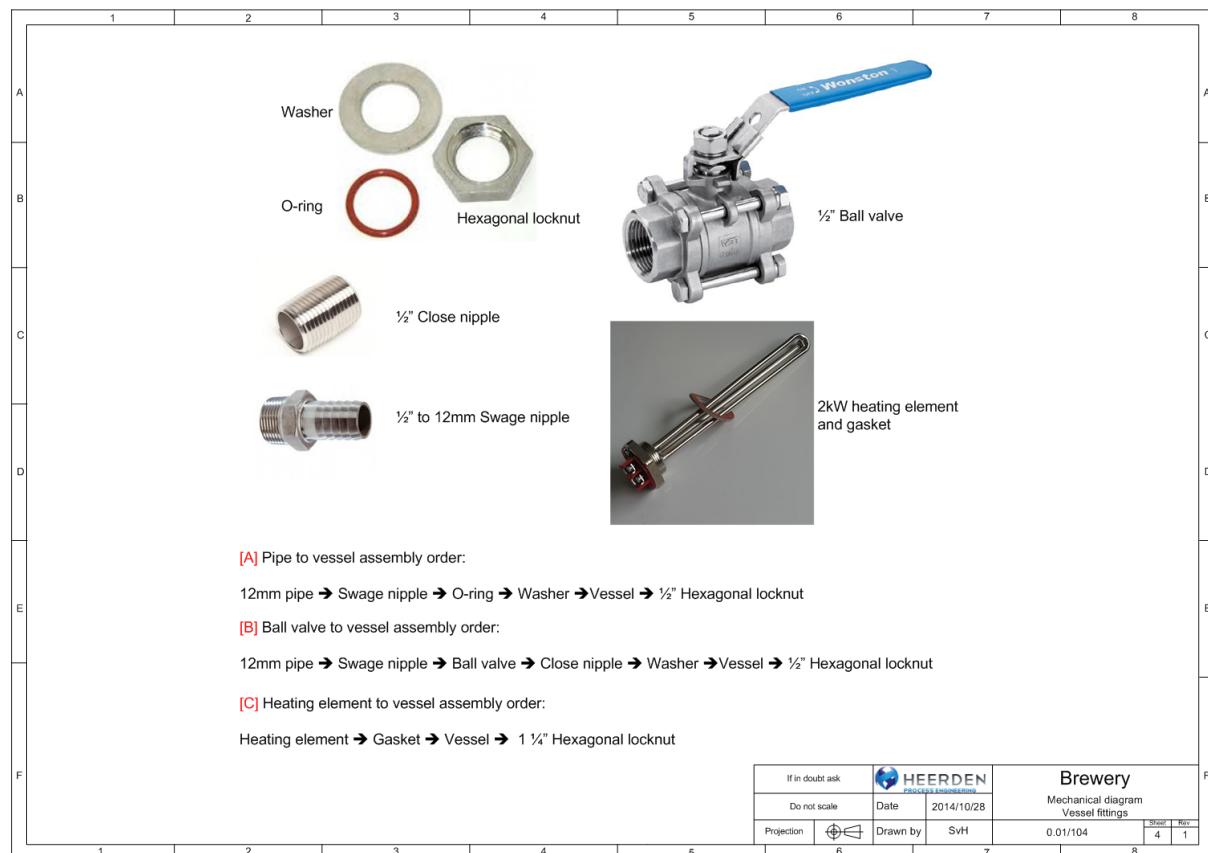


Figure 4.4: Vessel fittings

4.5 Pumps and valves

For a HERMS, pumps are essential to transfer process liquid. Two pumps will be required. The design of the pumping and valve system goes hand in hand. Solenoid valves are the most economical valves for open and close action. Further plastic solenoid valves are half the price of brass valves, but have a minimum operating pressure of 0.21 bar to function.

For the food and beverage industry it is recommended to use magnetically coupled pumps, as the process liquid is not in direct contact with the motor. This eliminates contamination. The most economical pumps with this function are washing machine pumps. They can accommodate the high temperature, but the amount of pressure they can deliver is not enough for the solenoid valve to open (* this needs to be verified with future tests). Higher rated, magnetically coupled, commercial beer pump are also available.

The Chugger brand of pump is one of the most economical beer pumps. It operates with 240 V power and the electrical operation is discussed in section 5.3.3. Its pump curve is given in Figure 4.5.

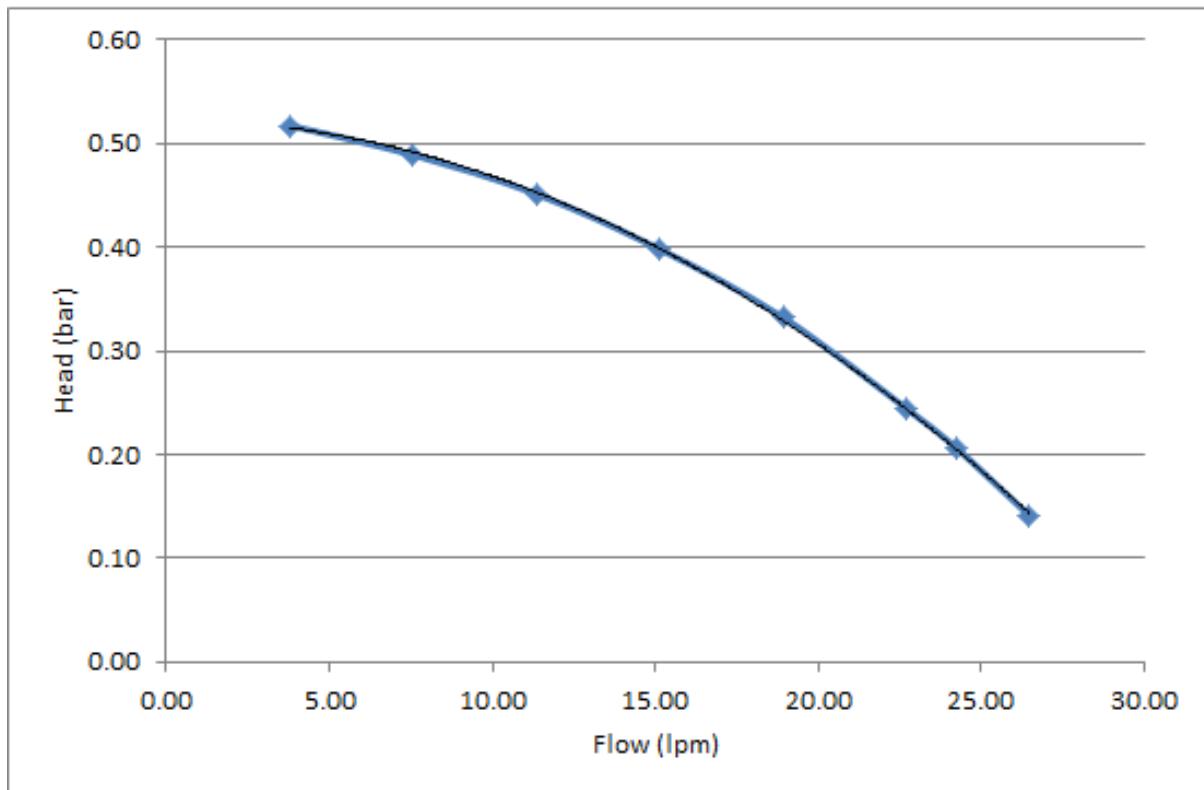


Figure 4.5: Pump curve

From this figure is can be seen that the pump will deliver the required pressure for the plastic solenoid valve, if the flow rate is below 24.22 l min^{-1} .

Weighing the option of cheaper valves versus more expensive valves. The plastic valve and Chugger pump configuration is used.

4.6 Heat exchangers

Heat needs to be exchanged in two areas of the brewery. The HERMS required a heat exchange coil inside the HLT. The material of construction is copper tubing with a diameter of 10 mm. SS tubing is recommended for the future.

Heat exchange in the KET section is also required (to cool the wort after the boil process step). A heat exchange coil could once again be immersed in the KET, but the use of an external plate exchanger is more energy efficient.

Chapter 5

Electrical design

This chapter will cover the design of the electrical system for the brewery. This will include an overview of electrical wiring. What will follow is a discussion on the heart of the brewery, the Raspberry Pi. Finally, a detailed description of the instrumentation will be given.

5.1 Overview

It must firstly be noted that electricity is very dangerous and can kill. Every precaution must be followed to design a system that is safe to build, commission and operate.

Figure 5.1 is an overview of the electrical wiring of the complete electrical system.

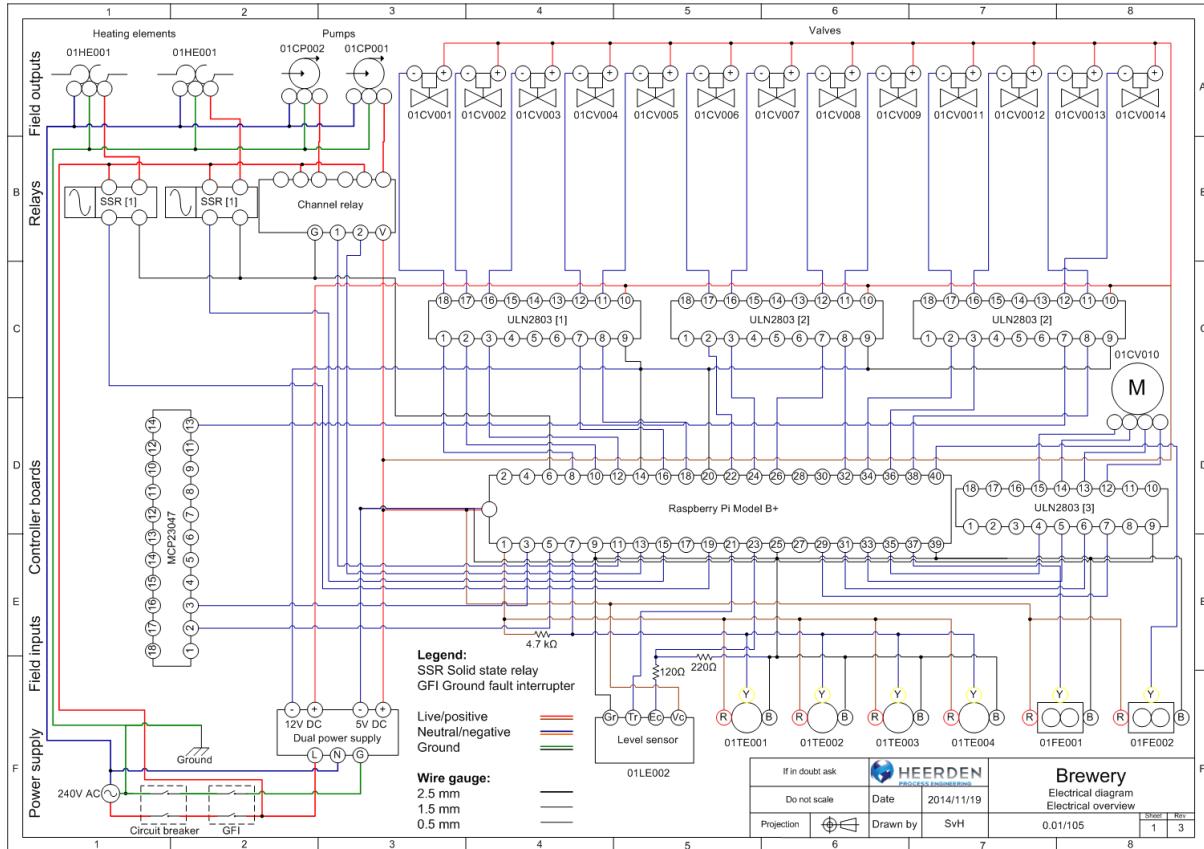


Figure 5.1: Electrical wiring

The high voltage components of the system are:

1. Circuit breaker
2. Ground Fault Interrupter (GFI)
3. Dual Direct Current (DC) power supply
4. Solid State Relay (SSR)
5. Mechanical channel relay
6. Heating elements
7. Pumps

The low voltage components of the systems are:

1. Raspberry Pi
2. Flow meters
3. Temperature sensors
4. Level sensors
5. Solenoid valves
6. Stepper motor
7. Darlington transistor chip (ULN2803)
8. Serial expander chip (MCP23017)

All the components will be installed in a control box, for safety and mobility.

5.2 Microcomputer

Hardware has been available for many years which enables the computers to receive inputs, process the response and send outputs to the outside world. In the last few years there has been a lot of progress in the development of microcomputers. These computers are lightweight, very compact, can access the internet, are well supported in the electronics community, but most importantly, they are excellent at interacting with the outside world. Table 5.1 list several microcomputers currently available on the market.

Table 5.1: Microcomputer list

System	Tag-line	Reference
Spark Core	“Stamp-sized hackable Wi-Fi module for interacting with physical things”	Spark (2014)
Cubox-i	“The smallest computer in the world”	SolidRun (2014)
Electric Imp	“The complete solution to easily connect any device to the Internet”	Electric Imp (2014)
OLinuXino	“Open Source Hardware Boards”	Olimex (2014)
Arduino	“An open-source electronics platform based on easy-to-use hardware and software. It’s intended for anyone making interactive projects.”	Arduino (2014)
Raspberry Pi	“Credit-card sized computer”	Raspberry Pi Foundation (2014)

The debate on which microcomputer is the best will not be settled here. As the title suggests, it was decided to used the Raspberry Pi to operate the brewery! It was selected due to its popularity in the market, ease of use and large development community.

5.2.1 Raspberry Pi

The Raspberry Pi is an ARM based microcomputer. It was development as a teaching tool to inspire a new generation of engineers to create electrical systems. Its complete specification is given in Table 5.2 and the General Purpose Input Out (GPIO) pin layout is given in Figure 5.2 (Raspberry Pi Foundation, 2014).

Table 5.2: Raspberry Pi Model B+ specifications

Specification	Details
Chip	Broadcom BCM2835 SoC
Core	ARM11
GPU	Dual Core VideoCore IV® Multimedia Co-Processor. Provides Open GL ES 2.0, hardware-accelerated OpenVG, and 1080p30 H.264 high-profile decode. Capable of 1Gpixel/s, 1.5Gtexel/s or 24GFLOPs with texture filtering and DMA infrastructure
CPU	700 MHz Low Power ARM1176JZFS Applications Processor
Memory	512MB SDRAM
Operating System	Boots from Micro SD card, running a version of the Linux operating system
Dimensions	85 x 56 x 17mm
Power	Micro USB socket 5V, 2A
Ethernet	10/100 BaseT Ethernet socket
Video Output	HDMI
Composite	RCA (PAL and NTSC)
Audio Output	3.5mm jack, HDMI
USB	4 x USB 2.0 Connector
GPIO Connector	40-pin 2.54 mm (100 mil) expansion header: 2x20 strip. Providing 27 GPIO pins as well as +3.3 V, +5 V and GND supply lines
Camera Connector	15-pin MIPI Camera Serial Interface (CSI-2)
JTAG	Not populated
Display Connector	Display Serial Interface (DSI) 15 way flat flex cable connector with two data lanes and a clock lane
Memory Card Slot	SDIO

The software for the Raspberry Pi, is installed on the Micro SD card. A WiFi adapter was inserted in the USB. This enabled the user to communicate wireless with the Raspberry Pi. From the 40 pins, 27 were available for GPIO pins. This was used to drive all the relays and read the sensors.

There are however not enough pins to accommodate all the inputs and outputs of the brewery. GPIO 2 and 3 are reserved for the I2C interface. The 16 channel MCP23017 is a I2C chip, and will be used to expand the pins.

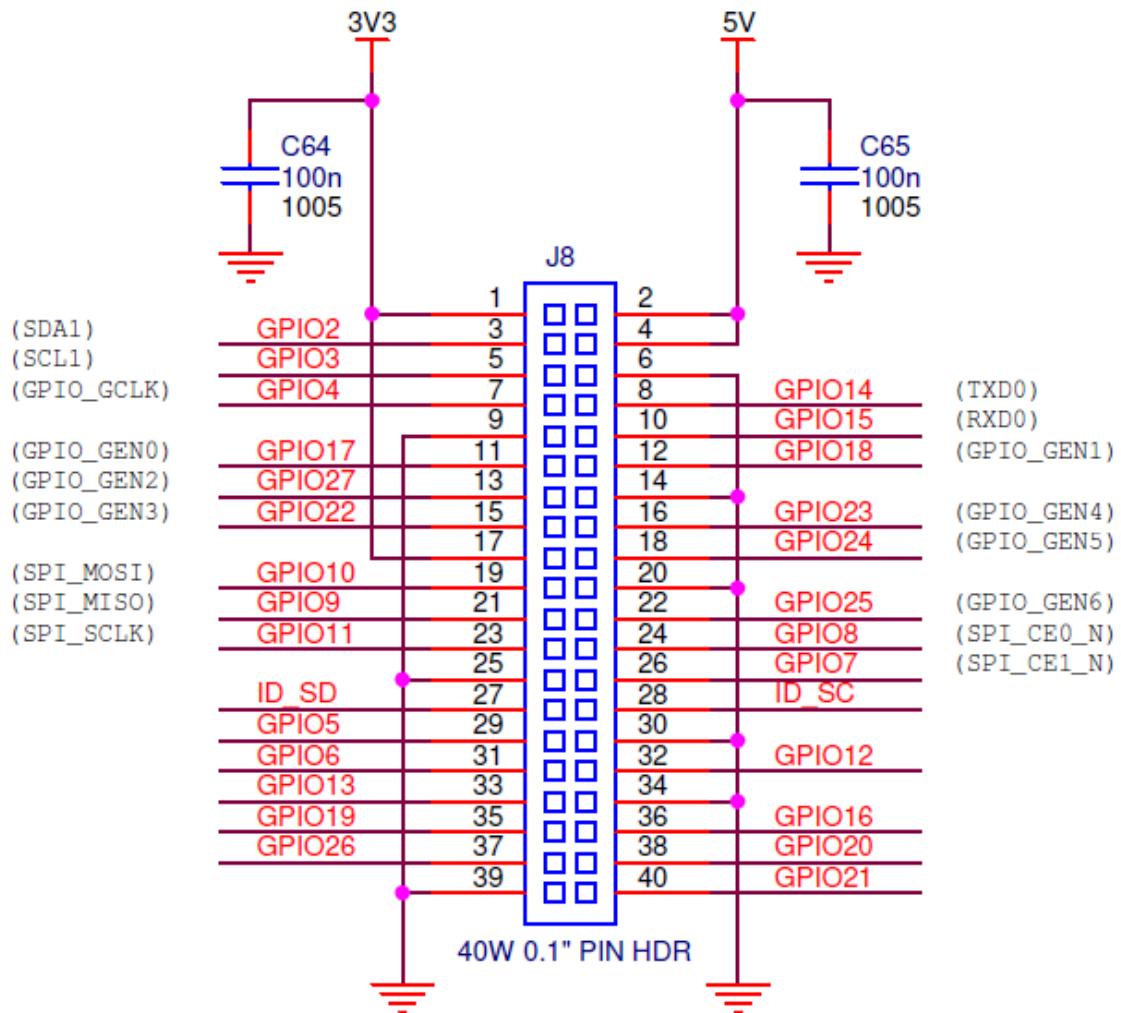


Figure 5.2: Raspberry Pi Model B+ pin layout

5.3 High voltage system

5.3.1 Power supply

In South Africa, power is supplied to domestic users at 240(220) V Alternating Current (AC) and 50 Hz (Eskom, 2014) and is received from a wall socket. Each country has its own code and should be checked accordingly.

Working on a process with a fluid medium, there is always a chance that the operator can be electrocuted. Current thus needs to pass through a ground fault interpreter (GFI) first. If the current drops by more than 5 mA, the GFI will trip the power to protect the operator. Next, to protect the electrical equipment, the current passes through a 32 A circuit breaker.

Current enters the control panel and live, neutral and ground lines are connected to their respective buses.

To ensure a dedicated supply of DC power for the low voltage systems, a dual power supply is installed; it supplies 12 V and 5 V. The Raspberry Pi was safely supplied with 5 V from this power supply.

5.3.2 Heating element

To heat the HLT and KET, heating elements are required; the elements will draw power from the live and neutral buses. In every live line there is a SSR to switch the element on and off.

5.3.3 Relays

The Raspberry Pi cannot control AC devices directly and require a relay to perform this task. A mechanical channel relay, which functions with solenoids, are used to switch the pumps. A 4 channel relay is used, but only 2 of the channels are used in this design.

The heating elements need to be switched on and off more frequently and mechanical relays will wear down quickly. An SSR is an electrical relay with no moving parts. It is already configured with triac components. A dedicated SSR for every element is used.

5.4 Low voltage system

This section covers most of the instrumentation that requires low voltage to operate. Custom program scripts have been created to test every instrument.

5.4.1 Flow meter

A very simple flow meter is used, which uses a pedal wheel to operate. The wheel turns faster as the flow rate increases, and the frequency in which a pulse is generated also increases. A pull up resistor is required to sense the pulses. An external resistor can be connected, but the internal pull up resistors of the Raspberry Pi was activated. Once a pulse is received, a program calculates the frequency and multiplies it by a calibration factor to give the flow rate.

5.4.2 Temperature probe

As already mentioned, both analog and digital probes where considered. The Raspberry Pi can, however, only accept digital signals. With the use of the MCP3008 I2C chip, analog signals can be converted to digital signals. With both the mechanical and electrical constraints weighted, the DS18B20 water proof sensor was selected.

The DS18B20 sensor uses the 1-Wire protocol to communicate with the Raspberry Pi and needs to be connected to the GPIO pin 4. Similar to I2C, the advantage of this protocol is that several devices can be connected to one pin.

5.4.3 Level sensor

Level sensing is required on the vessels for three reasons. They are needed to detect high level (pumps need to turn off to prevent over flow), low level (heating elements need to switch off to prevent damage to the elements) and the exact level position (required to maintain a level during sparging).

Three level devices were considered. Firstly, a flow switch can detect the level at various heights in the vessel, when its electrical circuit is broken. This is the most basic form of level detection, but several devices will need to be installed on every vessel. It was ruled out, because the amount of holes in the vessel should be minimised.

The second option is capacitance level detection. The capacitance of the fluid in the vessel can be measured to indicate the exact level in the vessel. An off-the-shelf solution that can accommodate the high temperatures of system, is not available. A custom devices needed to be build. This option is currently on hold, pending more research. The vessel design however includes glass level gauges, which means that a capacitance device can be fitted in the future.

A ultrasonic sensor was the level device that was finally selected. The HC-SR04 sensor was the most economical device and could be connected to the Raspberry Pi with ease. A program would send a signal to the sensor. This will activate the sensor to send a sound wave. The wave will bounce off the nearest object and will be received by the sensor again. Once received, the signal will send an echo signal to the program. The time difference between the trigger and echo is calculated. Half of this time is multiplied by the speed of sound though air, and measured distance is obtained.

The Raspberry Pi can only accept 3.2 V signals, but the echo signal is 5 V. This voltage was stepped down a configuration of two resistors. The ration between the resistors needed to be 0.51; 120Ω and 220Ω resistors is used.

5.4.4 Solenoid valve

A solenoid is an electrical device which moves a pin in a linear motion, from a minimum to a maximum position, or vice versa. In a valve assembly, a solenoid will constrict the flow of fluid through the valve. To protect the system, normal closed valves are used to shut down the system in an event that the valve fails. 12 V solenoid valves are used, but the Raspberry Pi is only cable of sending an output of 3.2 V.

The ULN2803 Darlington array chip was used to step the voltage up to 12 V.

5.4.5 Stepper motor

The operation of the valve 01CV010 is discussed in section 4.2. The Raspberry Pi cannot control motors directly, but the versatile ULN2803 chip facilitates this operation.

Inside a stepper motor, the rotor is surrounded by an array of electro magnets. To turn the rotor, the magnets are systematically switched on and off by a program. A full stepping sequence will be used (opposed to half stepping), as it produces the most torque for the motor. To control the rotation of the motor, the program executes a sequence for a specific amount of time.

5.5 Control box

All the GPIO pins of the Raspberry Pi were extended to the custom designed “Cherry Pie circuit board”, with a ribbon cable. 40 pin ribbon cables were not readily available on the market, thus a custom cables was made. For a prototype, a stripboard with a 2.54 mm grid was used. The design of the first prototype circuit board can be seen in Figure 5.3.

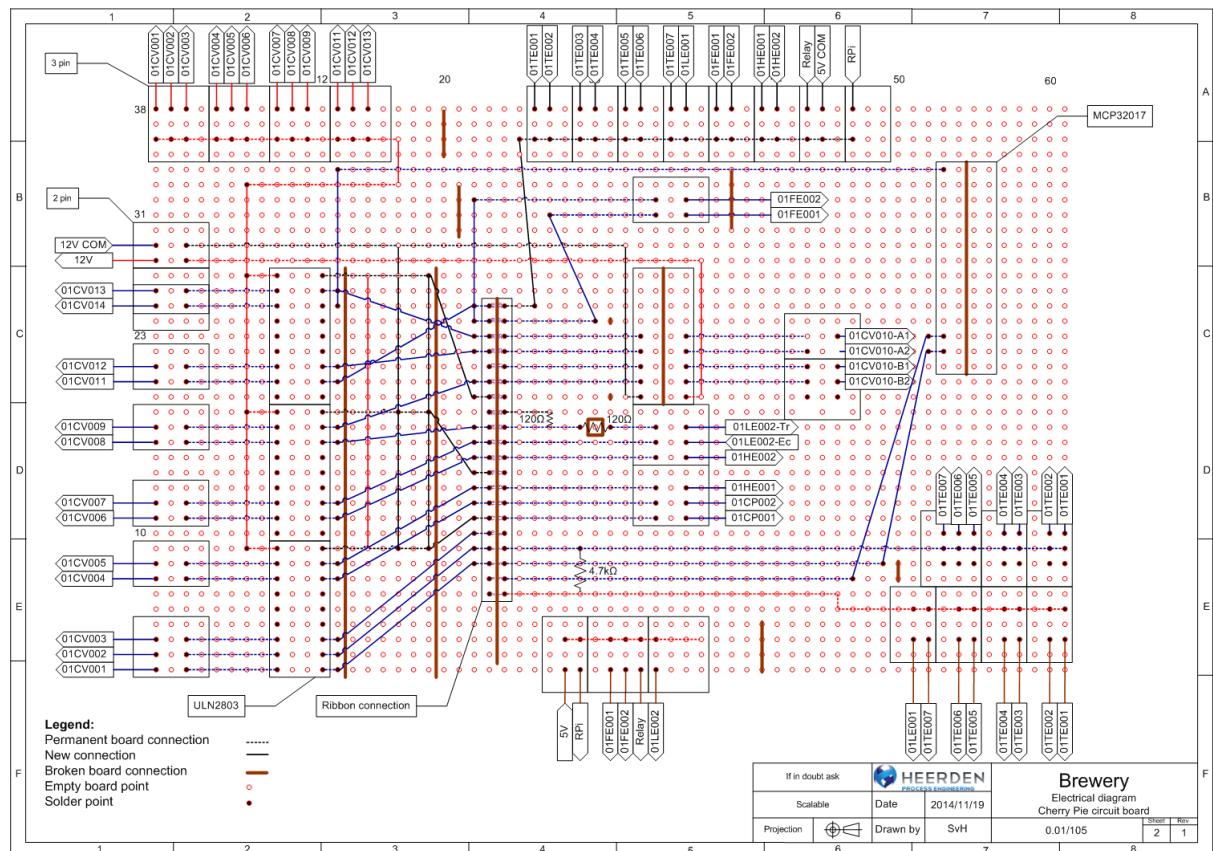


Figure 5.3: Cherry Pie circuit board

To ensure the safe operation of the overall electrical system, most of the electrical devices were enclosed in a control box. A plastic control box which is IP55 or NEMA12 rated, will protect the equipment against dust and water jets. The layout of the box is given in Figure 5.4.

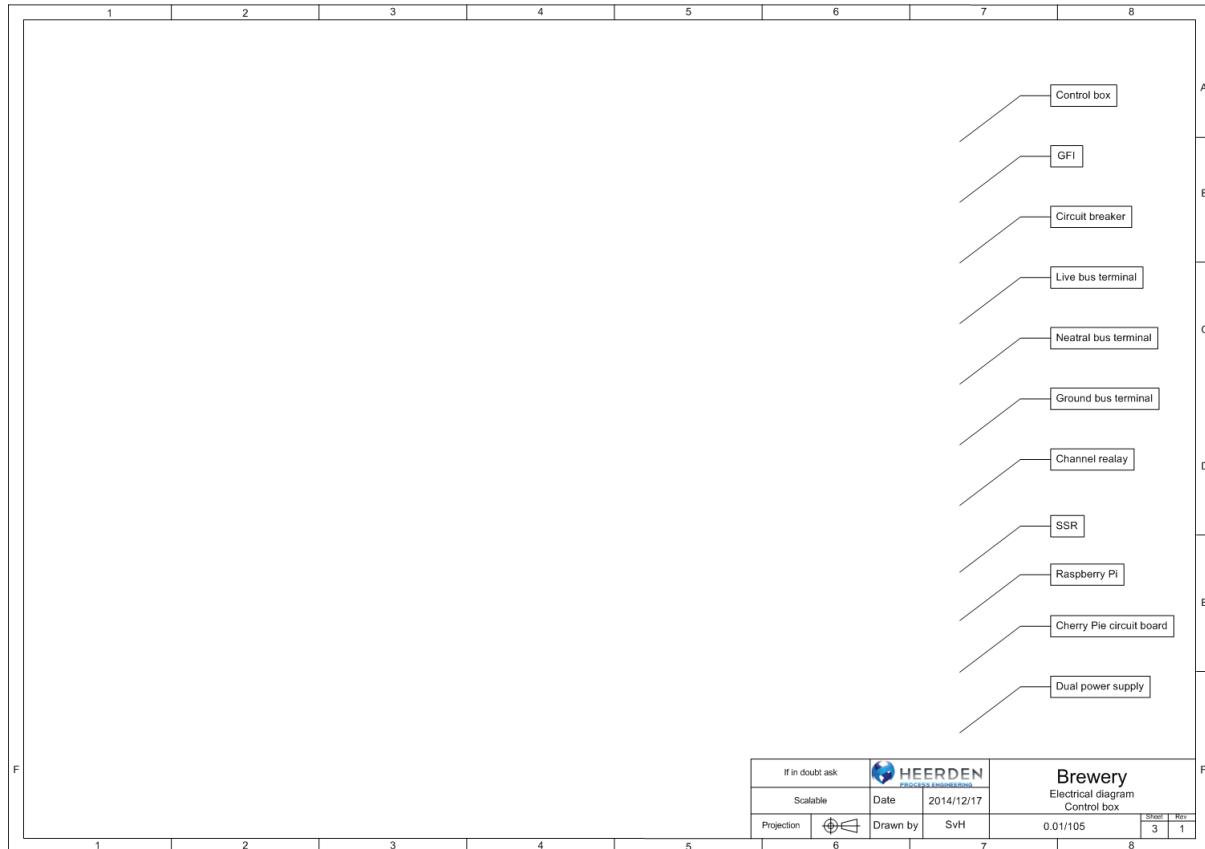


Figure 5.4: Control box

Chapter 6

Software design

With the mechanical and electrical systems configured, this chapter detail the software design required to control the brewery.

A disclaimer, programming experience is required to configure and modify the control system. Understanding of general operating system and programming commands is assumed, and will not be explained in this chapter.

6.1 Operating system setup

The Raspbian operating system is a Debian-Linux distribution and has been optimised to run on the Raspberry Pi, and will be installed.

To facilitate rapid development on Raspbian, either setup a Secure Sockets Layer (SSL) or Virtual Network Computing (VNC) to connect the Raspberry Pi and a remote computer. A VNC connection was chosen and to set it up, follow these steps:

1. configure a static IP,
2. install the TightVNC (2014) program on Rasbian and the remote computer (Windows or Java version is available) to serve a VNC,
3. configuring the Raspbian to boot TightVNC and
4. run TightVNC on the remote computer with the static Internet Protocol (IP).

6.2 Control system

The implementation of a control system is the most abstract concept for most home-brewers.

The first options is to use a soft Programmable Logic Controller (PLC) solution. Proview (2014) is such a open source process control system and there is a specific distribution for the Raspberry Pi. It is beyond the scope of this design guideline to discuss the advantages of such a system.

The second options is to create a custom control system to control the process. Both Python and C++ are powerful programming languages that is supported by the Raspberry Pi. It was decided to use Python for the main program. The web services will still use HTML, CSS and JavaScript (Ajax).

The wheel however does not need to be completely reinvented. The third options is to use one of several home-brewing control system that has been developed for the Raspberry Pi. They are listed in Table 6.1, however all they all fall short in the level of complexity, to control the processes described in Chapter 3.

Table 6.1: Open brewing software

System	Process	Primary language	Reference
Brewberry	Brew An A Bag (BIAB)	JavaScript	Brewfactory (2014)
BrewPi	Fermentation	Python	BrewPi (2014)
Mashberry	HERMS	C++	Mashberry (2014)
RasPiBrew	HERMS	Python	Smith (2014)

It was decided to use an exiting brewing control system; and extend it to control the HERMS and operate it with advance process control principles. The RasPiBrew was selected as the most feasible building block for the new control system.

If is worth listing other control systems, that inspired the design, in Table 6.2.

Table 6.2: Inspired systems

System	Process	Reference
BrewBot	Smart brewing appliance	BrewBot (2014)
PicoBrew	Automatic all grain beer brewing appliance	PicoBrew (2014)
OpenSprinkler Pi (OSPi)	Sprinkler valve control	OpenSprinkler Pi (2014)

6.2.1 RaspPiBrew

The RasPiBrew system was selected as the bases to build a new control system (Smith, 2014). It is programmed predominately in Python and can control more brewing subsystems than the other control systems. A control panel is generated for a browser by a server script, and can be accessed remotely. A smart phone app is also available.

A screen shot of the control panel can be seen in Figure 6.1.



Figure 6.1: RasPiBrew control panel

The following functions has been added to the new system:

1. Global brewing time counter
2. Logging of data in csv format

6.2.2 The repository

A repository was created on Github to manage the development of all the brewing software (van Heerden, 2014).

The important testing scripts for the inputs and outputs are listed in Table 6.3.

Table 6.3: Testing scripts

Instruments	Script name
Flow	flow.py
Level	level.py
Pump	relay.py
Actuated valve	motor.py

Chapter 7

Process control design

This chapter will use the philosophy that was defined in Chapter 3, to design algorithms to effectively control the brewery.

7.1 Controller design

RasPiBrew uses a Proportional Integral Differential (PID) control algorithm, that uses discrete time. The controller was tuned with the Cohen-Coon open loop method.

When temperature is controlled in the vessels, the temperature is not allowed to over-shoot the set point. There is however dead time in the system which influences the response of the controller.

More information to follow on PID control, tuning methods and troubleshooting!

Chapter 8

Recommendations

The primary control goal of the system was to control temperature and the overshoot issue must be addressed. There are several advanced methods that can be used to counter dead time in a system and improve the control: Model Predictive Control (MPC), Internal Model Control (IMC) and a Smith predictor.

The complete sequence of process steps needs to be programmed in the RaspPiBrew control system. The design functions for all the process conditions should also be programmed. The process conditions of any new recipe must be modified by these functions.

A very important output has not been added to this design, is an electric stirrer. A motor must be added on top of the MLT to facilitate mashing while stirring automatically.

The capacitance level sensor needs to be created.

The stepper motor valve and all the solenoid valves need to be commissioned.

More work is needed to elaborate on the steps in the control philosophy. A detailed component list is also required.

The completion of the Cherry Pie Brewery is still ambitious. The aim of this design guideline was to introduce enough concepts to inspire further development.

Chapter 9

References

- Arduino. Arduino, 2014. URL <http://www.arduino.cc>. Accessed: 2 Septmeber 2014.
- BrewBot. Brewbot, 2014. URL <https://www.kickstarter.com/projects/cargo/brewbot-the-smart-brewing-appliance>. Accessed: 2 Septmeber 2014.
- BrewersFriend. Introduction to rims and herms, 2009. URL <http://www.brewersfriend.com>. Accessed: 20 August 2014.
- Brewfactory. Brewfactory, 2014. URL <http://brewfactory.org>. Accessed: 1 Septmeber 2014.
- BrewPi. Brewpi, 2014. URL <http://www.brewpi.com>. Accessed: 1 Septmeber 2014.
- Electric Imp. Electric imp, 2014. URL <http://electricimp.com>. Accessed: 2 Septmeber 2014.
- Eskom. Understanding electricity, 2014. URL <http://www.eskom.co.za>. Accessed: 15 September 2014.
- Mashberry. Mashberry, 2014. URL <http://www.sansalinux.org/en/mashberry/index.html>. Accessed: 1 Septmeber 2014.
- Olimex. Olinuxino, 2014. URL <https://www.olimex.com/Products/OLinuXino/open-source-hardware>. Accessed: 2 Septmeber 2014.
- OpenSprinkler Pi. Opensprinkler pi, 2014. URL http://rayshobby.net/?page_id=5816. Accessed: 1 Septmeber 2014.
- J.J. Palmer. *How to Brew: Everything You Need To Know To Brew Beer Right The First Time*. Brewers Publications, 2004.
- PicoBrew. Picobrew, 2014. URL <http://picobrew.com>. Accessed: 2 Septmeber 2014.
- Proview. Proview, 2014. URL <http://www.proview.se/v3/>. Accessed: 1 Septmeber 2014.
- Raspberry Pi Foundation. Raspberry pi model b+, 2014. URL <http://www.raspberrypi.org>. Accessed: 5 August 2014.

- ReportLinker. Beer industry market research and statistics, 2014. URL <http://www.reportlinker.com>. Accessed: 25 November 2014.
- S Smith. Raspibrew, 2014. URL <https://github.com/steve71/RasPiBrew>. Accessed: 2 October 2014.
- SolidRun. Cubox-i, 2014. URL <http://www.solid-run.com/products/cubox-i-mini-computer>. Accessed: 2 Septmeber 2014.
- Spark. Spark core, 2014. URL <https://www.spark.io>. Accessed: 2 Septmeber 2014.
- W.Y Svrcek, D.P. Mahoney, and B.R. Young. *A real-time approach to process control*. Wiley, 2000.
- The Electric Brewery. Brew day: Step by step, 2014. URL <http://www.theelectricbrewery.com>. Accessed: 4 September 2014.
- The History Channel. How beer saved the world, 2011. URL <http://www.history.co.uk>. Accessed: 15 September 2014.
- TightVNC. Tightvnc, 2014. URL <http://www.tightvnc.com>. Accessed: 3 Septmeber 2014.
- C.W.S. van Heerden. Cherry pie brewery, 2014. URL <https://github.com/fugacity59/cherry-pie-brewery>. Accessed: 21 October 2014.